CRANFIELD UNIVERSITY

Simon Parsons

The aeration of clay soils in cricket

School of Applied Sciences

EngD
Academic Year: 2008 – 2012

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This thesis is submitted in partial fulfilment of the requirements for the degree of Engineering Doctorate

ABSTRACT

In the game of cricket good ball-surface interactions are essential and require a hard, flat surface. To achieve this the clay loam soil comprising the pitch is compressed and compacted using a smooth wheeled roller, which when combined with the drying action of the grass plant roots, causing the clay minerals within the soil to shrink, creates a high bulk density, hard surface on which to play.

High bulk density soils present difficult growing conditions for plants due to high mechanical resistance, reduced hydraulic conductivity and gas exchange capability. The hydraulic properties and gas exchange capability are linked to the connectivity and tortuosity of the pore network as well as pore size; all of which are diminished by compaction of the soil. Aeration is currently utilised as a tool to ameliorate the negative effects of compaction on the growing environment of the plant roots. Little research exists that describes the actions of aeration in clay loam soils. The current guidelines for aeration and the proof for its efficacy in cricket are based almost entirely on anecdotal evidence.

A diverse methodology was used to meet the project objectives. This diversity reflects the broad nature of the expectations of the cricket groundsmen from aeration of pitches as reflected in a survey of current practise undertaken during the project. Novel experimental methods were used to examine the effect of aeration on soil atmospheres in the laboratory and under field conditions. The laboratory experiment revealed that vertically-operated solid tines did significantly increase the rate of diffusion through the soil, however in the field, this rate increase was only apparent after significant rainfall. New methods utilising time-lapse photography and automated image analysis quantified the magnitude of swelling in a range of soils in response to increasing water content over time to a high degree of accuracy. A similar method was employed to examine the shrinkage of the same soils as the water content was reduced, examining not only the magnitude but also the cracking patterns formed. These experiments aimed to examine the soils natural ability to recover from compaction over time.

The soils natural ability to recover from compaction through shrink-swell and freeze-thaw was evident in the field trials. These field trials examined five diverse aeration treatments to examine the physical and biological effects they have on the soil. The field trials showed generally small and inconsistent effects on the physical properties of the soil from aeration treatments when compared to the natural processes of shrink-swell and freeze-thaw. One consistent effect from aeration was a 2% reduction in moisture content in one particular soil type. Aeration was found to have no effect on soil microbial biomass nor on soil organic matter content.

In a pot experiment examining the effect of aeration in a range of soil densities the total root mass was not diminished by increasing soil density but became increasingly concentrated upwards in the profile. Aeration was found to slightly increase the root mass but only in the highest bulk density treatment (1.90 g cm^{-3}) at depths below 75 mm.

A set of guidelines were developed based on the evidence garnered from the experiments with a clearly defined decision process for choosing the most suitable equipment for the treatment aim. It is hoped that these guidelines will provide an informative reference for current and future groundsmen to ensure the optimum use of often scarce and valuable resources when choosing an aeration treatment.

ACKNOWLEDGEMENTS

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Lastly my girlfriend, Bryony, for being head counsellor, able bodied assistant and for hauling me in when you felt the tug as I reached the end of my rope.

Generic descriptions of aeration processes and products have been used throughout where possible. Any reference to products, brand names or equipment types is not a recommendation of a particular manufacturer, model or brand by the Author, Supervisors or Cranfield University. The results of experiments in this thesis are limited to the experimental conditions that prevailed at the time of testing. Any recommendation is made in good faith and the Author, Supervisor and Cranfield University cannot be held responsible for the consequences of actions taken on this advice.

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LIST OF ABBREVIATIONS

AEP	Air-entry point
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
BS	British Standard
COLE	Co-efficient of linear extensibility
CT	Computed tomography
DAB	Digital audio broadcast
DMR	Depth of maximum resistance
ECB	England and Wales Cricket Board
ERP	Energy required to penetrate the soil
FM	Frequency modulation
GC	Gas chromatography
GPS	Global positioning system
ICC	International Cricket Council
ID	Identity
IOG	Institute of Groundsmanship
ISO	International Standards Organisation
KR	Keen-Raczkowski
LA	Linear aerator
LDPE	Low density polyethylene
MC	Microbial
MCC	Marylebone Cricket Club
MRP	Maximum resistance to penetration
PRFP	Performance related fee payment
PSWD	Potential soil water deficit
PTFE	Polytetrafluoroethylene
PTO	Power take-off
PVC	Poly vinyl chloride
RMSE	Root mean-square error
SH	Surface hardness
SP	Spiked roller
TLP	Time-lapse photography

USGA	United States Golf Associations
VOHT	Vertically-operated hollow tine
VOST	Vertically-operated solid tine
VOT	Vertically-operated tine

NOTATION USED

h_i	Height of soil at time i
m_0	Starting mass
r_0	Inner radius
h_{AEP}	Height of soil at air-entry point
A_{soil}	Total area of soil
V_{total}	Total volume
e	Void ratio
V_{voids}	Volume of voids
V_{solids}	Volume of solids
ϑ	Moisture ratio
V_{water}	Volume of water
θ	Gravimetric water content
D	Diffusion co-efficient
J	Diffusive flux
C	Concentration
t	Time
D_s/D_0	Relative diffusion co-efficient
D_s	Diffusion co-efficient in soil
D_0	Diffusion co-efficient in air
D_{a-b}	Diffusion co-efficient of gas a through reference gas b
y_n	Mole fraction of constituent n
Φ	volumetric flow rate
P_i	inlet pressure
P_o	outlet pressure
L	length of the tube
R	Radius of the tube
η	viscosity of the fluid

1 Introduction

The game of cricket has been played for centuries and as the game has evolved the tactics, skill and techniques of players have changed. The action of the playing surface, directed primarily through its interaction with the ball, has increasingly influenced both style and play (Adams *et al.*, 2005; James *et al.*, 2004). The Cricket groundsman is expected to provide a suitable surface to offer maximum enjoyment for the spectators and the participants by enabling the demonstrated skill and talents of the players from top internationals down to the village green.

The recommended guidelines in the UK for a match-prepared First Class standard pitch are a soil of 27-33% clay, dry bulk density of 1.65-1.75 g cm^{-3} and moisture content of 18-20% (Adams *et al.*, 2004). Current practise is to prepare a pitch that encourages pace (by ensuring maximum energy retention by the ball after contact with the surface) and predictable bounce (to enable safe and skilful play). This is achieved by evenly compacting the surface using a smooth wheeled roller throughout the spring before the playing season, as well as before and during a match. An extensive review and analysis of rolling techniques was carried out by (Shipton, 2008) resulting in a set of clear guidelines on rolling best practise.

The rolling and compaction of the surface creates an interesting cultivation problem, a deliberately compacted soil in which efficient rooting is of key importance for moisture removal to achieve the required hard surface but also to reduce crack formation through increased soil strength (Adams *et al.*, 1994). Aeration is employed to enable this and is applied after the end of the playing season. Aeration takes many forms, from the humble garden fork to sophisticated fluid injection systems, with the general aim of creating artificial macropores in the soil. The perception of the effectiveness of aeration is varied, the primary evidence for which is based upon individual trial and error, and the anecdotal, resulting in views of aeration ranging from ‘unnecessary’ to ‘vital’. Aeration is also used in cricket to combat problems brought about from a legacy of misguided management creating layered profiles, root breaks and shallow rooting. The variation in technique, application, and use requires a clear understanding of the scientific principles underlying its effects in order to provide effective guidelines for best practice at all levels of the game.

1.1 Cricket: the game and the role of the pitch

Cricket is the oldest national sport in the UK to have formal rules (Adams *et al.*, 1994). Drawn up in 1774 the rules have changed little in the last 200 years.

A cricket pitch is the prepared strip on which the batsmen and the bowlers play, with wickets at each end consisting of three upright stumps supporting two horizontally-laid bails. A cricket pitch is 20.12 m long and 3.66 m wide. Lines painted on the surface around each wicket are known as creases and determine batsmen dismissal and the fairness of ball delivery by the bowler (Figure 1.1).

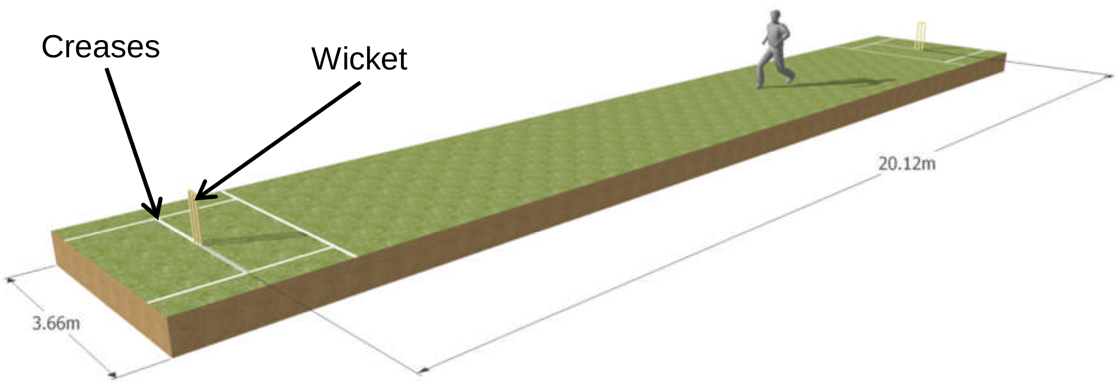


Figure 1.1 Three dimensional view of a cricket pitch showing creases and wickets.

The pitch is part of the square. The square is the area in the centre of the ground and consists of a number of pitches usually in various states of preparation for future matches. The outfield incorporates the remainder of the playing surface upon which the fielders arrange themselves subject to certain restrictions (Figure 1.2)

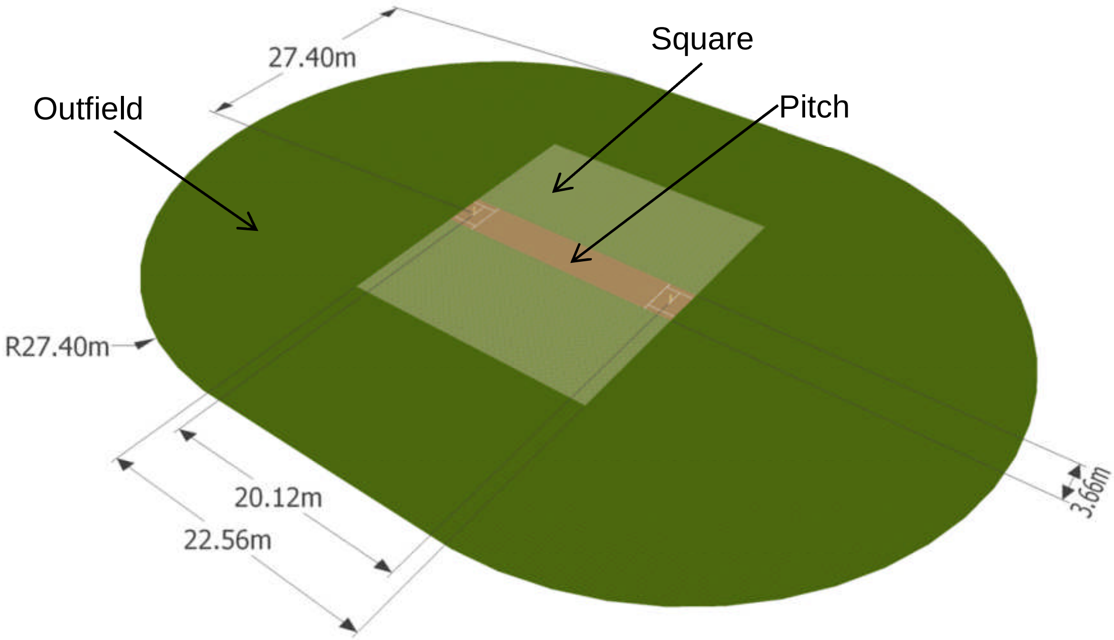


Figure 1.2 Three dimensional representation of entire cricket game area.

The game itself is played out between two teams of eleven players. Each team takes turns attempting to score runs after hitting a ball bowled by the opposing team. The objective of the game is to score more runs and achieve the complete dismissal of the other team within a set time limit. In a limited overs match (an over is six ball deliveries) the objective is to score the most runs within the allowed overs; complete dismissal of the opposing team is not a requirement for victory. International Test Match games are played over a maximum of five days and the winning team is required to have the highest number of runs and to have achieved the complete dismissal of the opposing team twice otherwise the game is drawn regardless of the number of runs scored.

The pitch is one of the defining factors in the quality, safety and enjoyment of a cricket game, both from the view of the players and the spectators, due to the intentional bouncing of the ball off the surface when bowled at the batsman. The influence of the pitch derives primarily from this defining ball-surface interaction where the quality of the prepared surface affects ball bounce, trajectory and pace (Adams *et al.*, 2005; James *et al.*, 2004). According to James *et al.* (2004):

Pace - the measure of the amount of speed the ball will retain after impact with the surface

Bounce – the expected rebound height the ball can attain after impact with the pitch

Generally a good pitch is considered to have high pace and high bounce subject to the consistency of the two processes. Consistency is a subjective attribute and has not been quantified (James *et al.*, 2004). If the pace and bounce are not consistent it makes the delivery of the ball too unpredictable for the bowler to strike the wicket and the batsman to strike the ball, if the pitches are too consistent then prediction of ball trajectory and speed becomes too easy and the game becomes overly biased towards the batsman and limiting to the bowler. Overall an optimum consistency is required of both pace and bounce which challenges both bowler and batsman without favouring either.

In cricket the pace and bounce of the surface are considered as critical parameters in playability. Both pace and bounce have been demonstrated to depend on three factors: vertical restitution of the surface, pitch/ball deformation and surface friction (James *et al.*, 2005). These three factors are almost entirely dependent on the physical properties of the pitch, particularly grass cover, water content, strength, hardness and bulk density of the soil.

1.2 What is the need for aeration?

Grass cover affects the playability of a pitch and allows game play to evolve as the surface is worn and damaged. The root system of the turfgrass plant is particularly important as it helps bind the soil surface, reducing crack formation, improving playing consistency. The build-up of dead grass plant crown and root matter (thatch) in the soil profile can eventually result in a pitch becoming unsafe. The increased organic matter increases the energy absorbance of the surface resulting in a pitch with poor bounce and slow pace as the ball retains less energy after impact with the pitch thus reducing the playability of pitches (Baker and Adams, 2001; Baker *et al.*, 1998b; Baker *et al.*, 1998c). This makes games dull for spectators and players alike. The burying of organic matter through successive topdressing each year can lead to layering where the soil cannot bind together effectively (Adams *et al.*, 1994) creating a horizontal break in the surface. The break has a deleterious effect on ball bounce and pace as well as potentially causing variability in ball trajectory such that neither batsmen nor bowlers can tell where the delivered ball will travel increasing the risk of accidental injury. The turfgrass also performs an important function of soil moisture removal through evapotranspiration (Shipton, 2008), which in turn affects the bulk density and strength (Adams *et al.*, 1994). Turfgrass grown in compacted soils tends to have poor performance (e.g. low wear tolerance, low stress resistance) and shallow root systems because of factors including mechanical impedance to root penetration, unfavourable gaseous concentrations in the soil atmosphere and soil water, and impeded movement of water into the soil (Waddington and Baker, 1965). More densely compacted soils have reduced pore space, smaller average pore radii and reduced connectivity between pores which directly affects the soils ability to transport water and achieve effective diffusion and exchange of gases potentially leading to anoxic or hypoxic environments and the possible toxic build-up of waste products (Lipiec and Hatano, 2003; Horton *et al.*, 1994; Stępniewski *et al.*, 1994).

The grass is essential for the safe and reliable performance of any cricket pitch. Various mechanical treatments exist to try and counteract many of the negative effects on grass growth attributed to compacted soils. The application of these treatments is called aeration (or aerification or core cultivation). The effectiveness of these treatments on cricket pitches is a matter of debate; some groundsmen choose not to aerate at all with, seemingly, no ill effects to their pitch, whilst others assert that proper aeration is essential to maintain the health and vitality of the grass cover.

1.3 What is aeration?

Rieke and Murphy (1989) defined aeration as a ‘mechanical means of selectively tilling the soil without destroying the turf’ and listed the objectives of aeration as:

1. Relieving soil compaction
2. Aiding in thatch control
3. Disrupting undesired soil layers
4. Preparing soil for topdressing and overseeding
5. Enhancing the penetration of fertiliser and other chemical inputs
6. Stimulating turf density by severing stolons and rhizomes.

The variation in design and action of aeration machines reflects the broad objectives that are expected of it. The most prevalent forms of aeration are hollow tine, solid tine, spiking, slicing and water/air injection. Each machine is generally more suited for achieving some objectives more than others.

1.3.1 Slit/Knife tines

Slit and knife tines are utilised as rotating blades that cut vertically through the soil. Pedestrian units will penetrate 75-150 mm into the soil and tractors driven units up to 300 mm

Figure 1.3 Example of a tractor mounted slit/knife tine machine (Wiedenmann, 2009).

Variations on this include rotary decompactors that organise the time of entry of neighbouring tines to occur sequentially rather than simultaneously which has the effect of shaking the soil as the first tine pushes the soil one way which is then pushed back the opposite way by the entry of the neighbouring tine shortly after.

Use of these machines in shrink-swell soils carries a risk that if carried out too close to spring-summer the slits may reopen in dry conditions as they will be inherently weaker than the surrounding soil (Brown, 2005).

1.3.2 Solid/Spike tine

Solid tines come in various shapes and sizes. Chisel, star, solid and needle tines are common. Solid and needle tines consist of a tapering cylinder of solid metal (Figure 1.4) generally 75-230 mm in length, and varying in diameter from 7-12.5 mm.

Figure 1.4 Example of a solid tine.

Star tines are fluted to give a star-shaped profile aimed at increasing the wall area of the tine hole whilst reducing the compaction surrounding the hole. Chisel tines have a large flat triangular shape that create a slit-like cut in the profile (Figure 1.5).

Figure 1.5 An example of a star tine showing the distinctive fluted structure (left) and a chisel tine (right) (steelmaster.co.uk, 2012).

The tines are driven into the soil either using a ‘drum-type roller’ or ‘cam-action’ machine. The drum-type roller has the spikes arranged on a drum and the weight of the machine drives the tine into the soil as the drum rotates across the surface. The drawback of this machine is that the entry angle of the tine is opposite to the exit angle which creates a lifting action on the soil; with repetitive treatment this can cause a break in the soil profile or tear parts of the surface away completely as they are lifted by the action of the machine. Consequently, this machine type is no longer recommended for cricket (ECB Staff, 2007). At one time they were very popular and many machines are still used.

The cam-action machines are designed so that the tine enters the soil vertically and is retracted vertically to avoid heave problems associated with the drum-roller. Some cam-action machines will allow the user to set a certain amount of heave, similar to the drum-roller, whereby the machines deliberately alters the angle of the tines when they are fully penetrated to lift the soil slightly, which, if done in the right conditions, causes the soil to fracture creating additional pore space. For the same reasons as the drum roller, the use of heave is not recommended in cricket as it may encourage the formation of breaks in the soil profile as well as potentially disrupting surface planarity.

It is important to note that solid tines displace the soil, they do not remove it. As such the artificial macropore is created at the expense of the porosity of the surrounding soil.

1.3.3 Hollow/coring tines

Hollow tines consist of a tapered metal tube open along one side which is driven into the profile removing a plug of soil as it is extracted (Figure 1.6). The plug of soil in the tine is then forced from the tine by the next penetration and cast out onto the surface of the soil. Hollow tines vary in width from 10-22 mm and 60-125 mm length. The same equipment that is used to mount the solid tines can also be used for hollow tines.

Figure 1.6 An example of a hollow tine showing the hollow interior and open side for core ejection (steelmaster.co.uk, 2012)

Hollow tines are commonly used on golf courses particularly for use in controlling the build-up of organic matter (thatch) and decompaction of the soil (Carrow, 2003; McCarty *et al.*, 2007; Guertal *et al.*, 2003; Murphy *et al.*, 1993; Murphy and Rieke, 1994). The removed plugs of soil are swept up and removed and fresh soil is spread over the surface to replace it.

The use of hollow tines is no longer recommended in cricket due to the inefficiency of the task (as the plugs of soil do not eject easily from the tine and have tendency to get stuck) as well as difficulties associated with filling the subsequent holes with sufficient loam to achieve a flat and level surface again (ECB Staff, 2011; Woods, 2012).

1.3.4 Deep Drill

Drum-roller and vertically operated tines, both hollow and solid, have been associated with compaction around the tine hole as the tine is thrust into the soil. As the working depth (the depth of maximum penetration of the tines) increases a greater force is needed resulting in greater compaction around the tine hole. An alternative method is the Deep Drill which uses large drill bits to bore into the soil up to a depth of 450 mm with drill bit diameters between 10-20 mm (Figure 1.7).

Figure 1.7 A Deep Drill machine showing the array of drill bits (left) and the machine in action (right).

The benefits of the drill are reduced side wall compaction and smearing as the drill bores rather than thrusts through the soil.

Like hollow tines the hole can be backfilled either by hand or using the “Drill and Fill” modification of the Deep Drill which automatically backfills the hole with fresh soil. The “Drill and Fill” technique works best with sandy soils commonly found on golf courses. Attempts to use the “Drill and Fill” on cricket wickets using clay loam is less successful as the soil cannot be compacted into the holes to a sufficient degree by the machine to avoid slumping the following year causing a golf ball like appearance to the pitch (King, 2008). The consequences of this would be erratic bounce if the ball impacts one of the partially filled holes as well as being aesthetically displeasing as the grass will tend to grow in tufts out of the hole (Woods, 2012). As such the holes must be manually filled and compacted to avoid this; a process which is extremely laborious and time consuming.

1.3.5 Air/Water Injection

There are several forms of fluid injection systems. Air injection systems come in two general forms, air injection at a relatively low pressure (air is introduced at 88 l min^{-1}) that is a modification of standard solid tines. Or air injection at very high pressures (approximately 6-20 bar) using a single large tine. The first system is essentially identical to standard solid tine using a cam-action machine. The tines have a tube running through the centre terminating in a hole in the side of the tine. At the other end the tine is connected to a compressor. A mechanical switch ensures that the air injection is activated only at maximum tine penetration.

Figure 1.8 Tine from the Sisis Javelin Aer-Aid machine showing the side hole for air injection.

The second system utilises air at much higher pressure injected through a single tine which acts to inflate the surrounding soil. This forces the soil apart to create fissures and pore space, the action of which is visible above ground as the surface rises after the initial injection and then sinks back down as the air escapes.

Water injection uses high pressure (345 Bar) jets applied from the surface that force the water into the soil. The working depth of the machine is determined by the amount of time and number of injections in the same position (the machine applies bursts of water rather than a continuous flow) and is reported as 200-500 mm by the manufacturer. The action of the water is designed to create holes in the soil as well as forcing the soil apart from the pressure of the water. The additional benefits are that liquid wetting agents designed to increase the water holding capacity of the soil can be injected with the water, which is of benefit to those on a sand dominated soil. Water injection has been associated with separating the fine and coarse particles in sandy soils adjusting the particle size distribution in places and consequently the pore size distribution resulting in negative effects on drainage as pores become blocked by fine particles carried by the water from elsewhere in the profile (Brown, 2005).

1.3.6 Vertical mowing\Linear Aeration\Deep Scarifying

These processes are all essentially the same but have varying depths of operation. Vertical mowing is generally a surface operation whilst linear aeration and deep scarification will penetrate the soil to a certain depth. The machinery consists of rotating knives turning in a vertical plane on a high speed horizontal shaft. The blades may be fixed or free swinging and vary in thickness from 1-2 mm.

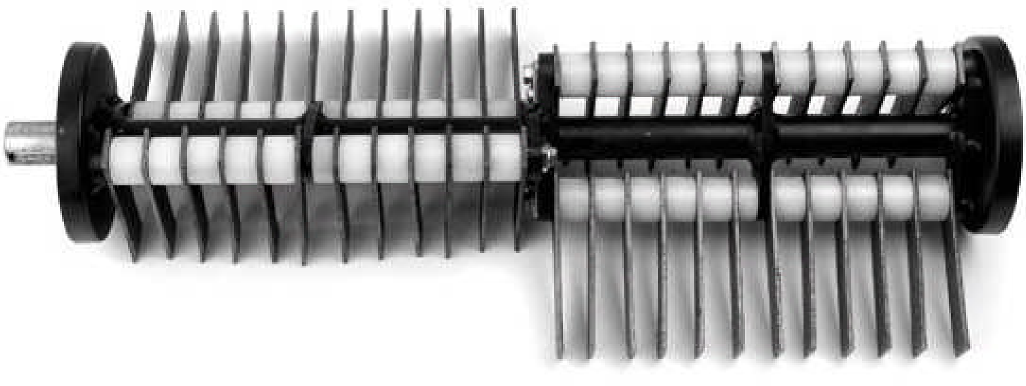


Figure 1.9 Set of scarifier blades mounted on a horizontal shaft (Comm 42, 2012).

The blades impact the soil to cut and remove surface and shallow buried organic matter, and, sever and lift procumbent growth. The maximum depth of action is determined by the engine/hydraulic power of the unit but can be up to 50 mm. It is normally recommended to set the machine only to the lowest depth of thatch in the profile when using it on a cricket pitch, for the same reason as slitters are not recommended, as the soil may become weakened enabling the formation of cracks (IOG/ECB, 2006).

1.4 Autumn maintenance and current aeration guidelines in cricket

ECB Staff (2011) are the latest recommendations for the maintenance of a cricket pitch year round. In this, autumn renovation is stated as the foundation for quality pitches for the forthcoming season. The guidelines suggest the following actions in order of application:

Scarification
Overseeding and topdressing
Aeration

Scarification replaces traditional raking of the surface to remove organic matter. It is also effective at controlling the invasive *Poa annua* grass species; *Poa annua* is shallow rooting and as such the root system is severely damaged by scarification which will either kill the plant or severely reduce ability to compete with the planned grass cultivars. Scarification consists of a motorised unit of fast rotating vertical blades that cut into the soil up to a recommended maximum depth of 12 mm (dependent on the power of the machine used and durability of blades). This has the added benefit of providing an improved surface for good soil-seed contact aiding germination rates. The aim is to remove as much organic matter as possible to prevent it building up in the profile. This is done to avoid deleterious effects on ball bounce and pace (Baker and Adams, 2001; Baker *et al.*, 1998b; Baker *et al.*, 1998c) and the potential formation of layering in the profile due to reduced binding strength of topdressing when applied on top of surface organic matter (Adams *et al.*, 1994).

Overseeding and topdressing are the application of fresh soil and new grass seed on the surface to replace that removed by the scarification process and ensure a good level of grass cover. The selection of the topdressing material is of primary importance. Shipton (2008) reported on 20 commercially available soils for use on cricket pitches with distinctly variable properties particularly regarding mineralogy and the extent of shrink-swell. Matching soil for topdressing to retain compatibility with the existing soil is a relatively recent advancement. The guidelines state the importance of choosing the right soil and recommend sending a sample for testing in an approved laboratory, which has a financial cost as well as requiring an understanding of the results. If the soils are not properly matched they may not bind together or the differing shrink-swell characteristics will cause the soils to break apart as one shrinks more rapidly than the other. The burying of organic matter and improper selection of topdressing, creating breaks, are known as layering and present considerable problems for groundsmen in maintaining quality pitches. A break in the profile presents numerous problems. The formation of the breakage can sever the roots restricting the growth of the plant. The growth of roots through the profile will favour the path of least resistance which in the case of layering in the profile will be horizontal, along the break, as opposed to vertically down through the profile as desired. Water penetration can be impeded resulting in pitches that are wet above the break but still crumbly and dry beneath. Finally, and most importantly, the breaks in the profile act to cushion the impact of the ball reducing the pace and bounce of the pitch (Adams *et al.*, 2001).

Soil cannot be mined or quarried specifically in the UK and suppliers of cricket loam must source their products from whatever is available from construction projects and quarrying for other minerals. As such buying the same brand of cricket loam does not ensure that the soil itself is always the same.

Aeration is only applied once the grass has germinated and the topdressing has bound sufficiently to the surface so that it will not get picked up by the aeration machinery as it moves across the pitch. This is usually around mid-November when temperatures have dropped so that the main growing opportunity has passed and the soil is generally wet enough so that the tines can penetrate. Attempting to aerate if the soil is dry will result in reduced penetration, increased wear and may break the machine because of the high soil strength of the clay loams used in cricket pitches when dry. When the soil is dry it will tend to fracture rather than deform, requiring far greater amounts of energy as it necessitates the shearing of the soil across the entire surface area of the newly formed crack rather than just deforming and compressing a small volume which would occur if the soil was in a plastic state (Marshall *et al.*, 1996).

Current guidelines recommend the use of solid tines using a cam-action machine with no heave or the deep drill technique depending on the objective. When aerating as routine the solid tine is recommended to as maximum a depth as possible, minimum 100 mm, using small diameter tines to minimise side-wall compaction.

The deep drill is recommended by (ECB Staff, 2011) in addition to regular solid tine aeration as a means of penetrating deep into the profile. Back filling the holes with fresh loam is seen as a method of removing thatch and solving layering problems as the fresh loam and root growth down the tines will act as "nails" to bind the layers together (Figure 1.10) however there is no empirical evidence for this (ECB Staff, 2011; Woods, 2012). The deep drill however requires a specialist operator and the holes will need to be filled by hand resulting in a tedious, laborious and expensive procedure.

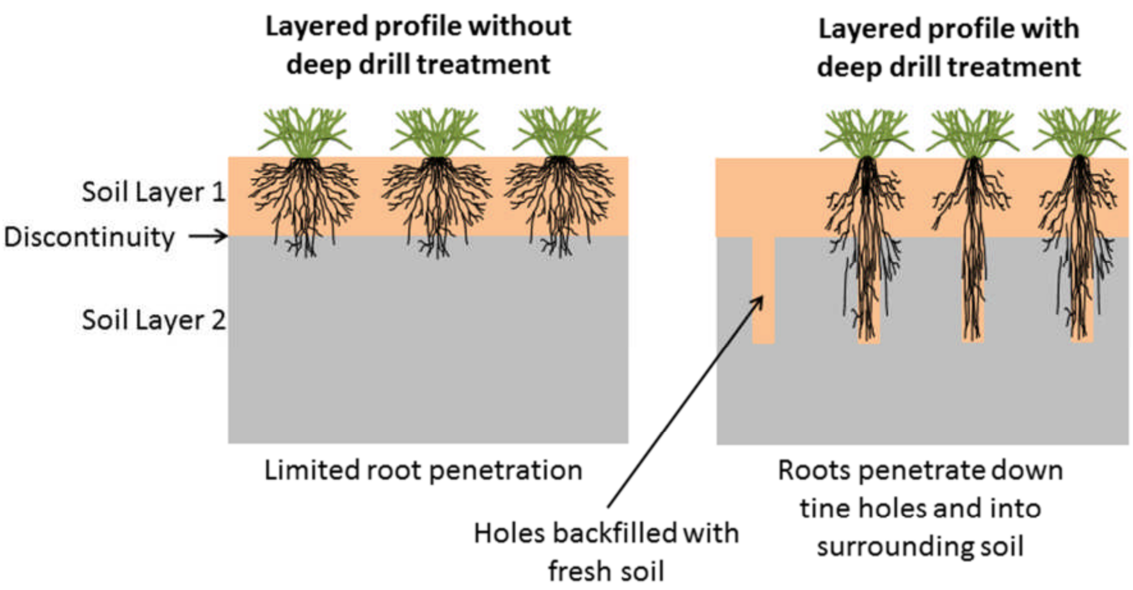


Figure 1.10 Illustration of the theoretical binding together of a layered profile using increased root penetration from deep drill aeration.

When choosing which aeration technique to use and when to start the current guidelines suggest taking a core but do not mention what the criteria are and what the groundsmen are looking for.

1.4.1 Fraise topping and mowing

If layering in the pitch is so severe that the groundsman is considering hollow tining, the guidelines suggest using fraise mowing and fraise topping as an alternative. The fraise mower is a tractor mounted surface planer which removes the soil to a specified depth of up to 40 mm on each pass. The soil is then removed by conveyer belt directly onto a tractor for removal (Figure 1.11).

Figure 1.11 Fraise mower in use showing the trench behind where the soil has been cut away with the waste soil deposited by conveyer onto a waiting trailer (Bancroft Amenities Ltd, 2012).

Three methods are recommended that include this machine:

1. Fraise topping
2. Fraise topping and cultivation
3. Fraise mowing

Fraise topping involves stripping the soil of the grass surface and underlying soil to remove all offending layers. A shallow tilth is then established up to 25 mm in depth and the new compatible soil is added, levelled, fertilised and seeded. With careful management and completed at the right time (early autumn) full grass cover can be established in 3-4 weeks and cricket can commence in the following season as the square has not been re-laid and so does not need to settle.

Fraise topping and cultivation is recommended for deep root breaks though no depth is specified (IOG/ECB, 2006). The principle is the same as fraise topping in that the grass surface and offending soil is removed. Instead of creating a fine tilth to 25 mm however a more robust method is employed, such as a power harrow, to cultivate the layers and indigenous soil into a fine tilth (so as to avoid trapped air pockets) which is then graded and levelled before the rebuilding of the pitch as above. The greater disturbance of the underlying soil means the pitch may underperform in the following season but should improve the next season.

Fraise mowing is where the machine is set to a level that removes only the vegetation. This is similar to scarification in its effect as it removes the shallow rooting *Poa annua* and any thatch accumulations. It also removes the older ‘woody’ stems and crowns of rye grass but generally leaves the body of the plant intact for regeneration post treatment. This treatment can also be used to maintain surface levels and remove saddles (unevenness in the pitch that can develop from overzealous topdressing).

1.5 Aim of aeration in cricket

ECB Staff (2007) describe aeration as “one of the most essential requirements of managing a healthy soil profile in particular relieving the dense consolidation …” Benefits from relieving soil compaction include increased rooting density and depth, increased infiltration and improved gas exchange which will alleviate much of the identified problems in Section 1.2 for growing grass in these soils. Unfortunately solid tining is generally not considered to relieve compaction in soils (Brown, 2005; Rieke and Murphy, 1989). Solid tine aeration increases localised compaction (Rieke and Murphy, 1989; Murphy *et al.*, 1993; Petrovic, 1979) and does not reduce compaction overall. It is unclear how it relieves the dense consolidation in cricket pitches as stated in the guidelines and if it does not, what other effects does it have (if any) that have led to it being regarded as essential?

The guidelines reveal two aims from aeration in cricket soils:

- Routine application to relieve the effects of consolidation in the profile
- Repair or neutralise the effect of layering in the profile.

This project will focus primarily on aeration as a routine treatment with the aim of gaining a greater understanding of the factors which impede grass growth in compacted clay soils and from this provide a quantifiable basis of assessment for aeration treatments linked to the ability of various machines to counter or alleviate the negative growing conditions.

1.6 Structure of cricket governance

The International Cricket Council (ICC) is the international governing body of cricket. The ICC has three tiers of membership: full members, associate members and affiliates. Currently there are 10 full members (between which Test matches are played), 35 associate members and 60 affiliate members. The responsibilities of the ICC are to provide the organisation and governance of the major international tournaments (e.g. Cricket World Cup) and to appoint the umpires and referees for all Test, One-day international and Twenty20 international matches. The ICC also sets standards of discipline for international cricket and co-ordinates the anti-corruption and match fixing investigations.

Notably the ICC does not control bilateral fixtures between members, domestic cricket or the laws of the game. The rules of cricket are controlled by the Marylebone Cricket Club (MCC) in London.

The England and Wales Cricket Board (ECB) is the governing body in England and Wales and was formed in 1997 to combine the roles of the Test and County Cricket Board, the National Cricket Association and the Cricket Council. In 1998 it also took responsibility for women’s cricket previously held by the Women’s Cricket Association. The ECB is a company limited by guarantee. This legal status allows the ECB to concentrate on maximising its funding for the sport instead of making a return to investors.

Governance of the ECB is provided by representatives from the 38 first class and minor counties and the MCC. It is headed by a 14 member management board. The ECB has numerous responsibilities, chief amongst them is responsibility for the England side - its funding, and commercial exploitation. The international side is one of the ECBs chief assets which it has successfully leveraged for considerable financial benefits in ticket sales, shared revenue from international games, sponsorship and broadcast rights.

Below the international level are 18 professional first-class county clubs, 20 minor counties cricket clubs (i.e. not first class), 6 MCC Universities (of which Cambridge, Oxford, Durham and Loughborough University teams are counted as first-class games when playing one of the 18 first class county teams) and below county level are a host of club competitions organised on a regional basis, of which the ECB premier league is the highest.

The club and county cricket boards are economically independent of the ECB but the county cricket boards are particularly reliant on ECB for funding to supplement any additional income revenue streams.

1.7 ECB Strategy

Business strategy has been defined as the ‘determination of the long-run goals and objectives of an enterprise and the adoption of the courses of action and the allocation of resource necessary for carrying out these goals’ (Chandler, 1993). The aim of all businesses is to satisfy the expectations of the stakeholders. In most business this is generally maximising profits. Not-for-profit organisations (NPOs), such as the ECB, are not driven by profit but to optimise funding in order to have sufficient surplus cash to achieve their objectives. It is the achievement of the objectives that satisfies their stakeholders.

For a sports organisation like the ECB, increased participation as fans and players at all levels of the game is the main goal together with sporting success, though the two are generally intrinsically linked. To achieve these objectives the ECB needs funding. Sources of funding for NPOs are diverse and generally those supplying the funds do not gain anything directly in exchange, for example, the government will give funds for reasons of anti-obesity or youth crime reduction not necessarily because they desire cricket to be the national sport of England. The main sources of funding are either funding bodies (such as the Government, Sport England) giving out grants or organisations looking to gain from association. These sources of funding may have limitations or conditions set upon them (for example the funds must be used for youth participation, female participation, disability access or racial integration) which may influence the strategic application of these resources. Because of this (Johnson *et al.*, 2011) recommends that responsibility for acquiring funds and decision making in the strategic planning process be handled centrally where responsibility and awareness of external influences can be more efficiently handled than in a more dispersed organisation. Sports organisations all produce similar products (although with different sports) and competition between them is for funds from national bodies, commercial partners and media rights. Of these sources, commercial partners and media rights are primarily driven in the size of the funds offered by the popularity of the sport. Hence increasing the popularity of the sport is one of the principal goals of the ECB strategy.

The organisation of the ECB is as a central body not only to govern the sport and increase participation in the sport, but also to negotiate and allocate funding to the sport that it receives from third party funding bodies. The ECB has several particular resources that it can leverage for extra income, particularly the national team since it owns the rights to the associated media broadcast income, sponsorship opportunities, ticket sales and memorabilia.

In leveraging its assets and negotiating for funding the ECB has been particularly successful in raising its turnover year on year (Table 1.1). The income from media rights dwarfs any other income stream and accounted for 73% of total income in 2010 and is of primary importance to ECB strategy. The increase reflects the effectiveness of a centralised body for attaining funding. Though media rights income dominates they have attempted to enhance the diversification of funding, such as in 2009 where the ECB gained the largest grant of any national governing body (ECB, 2009) for the development of grassroots cricket of £39 million spread over four years from Sport England.

Table 1.1 Annual turnover of the ECB from 1997 to 2010 where known. Actual figure and inflation adjusted figure. The retail price index was used as the basis for inflation values (Bank of England, 2012).

Year	Turnover (£million)	Inflation adjusted turnover (2010 prices) (£million)
1997	20.0	28.4
2006	77.0	86.9
2007	90.0	97.4
2009	114.5	119.8
2010	106.0	106.0

In 2005 the ECB set out its strategic goals in a document entitled ‘Building Partnerships’ (ECB Staff, 2005) detailing the strategy over the next four years to meet four key goals:

1. Effective leadership and governance
2. A vibrant domestic game
3. Enthusing participation and following
4. A successful England team

The document also included objectives allocated to various departments and partner organisations to achieve these strategic goals by 2009. The ‘Building Partnerships’ strategic plans come from the realisation within the ECB that up to that point most of the game’s planning was based on wish lists and well-intentioned, independent projects. Lacking a unified strategy this resulted in ill-defined roles, plans and responsibilities (ECB Staff, 2005).

The strategy was partly inward focused, reforming the ECB from a supportive role to a more focused, ‘customer-driven’ body dedicated to the success of the game at all levels. The remainder of the strategy was primarily focused on capturing public attention by boosting the success of the international team and through greater investment in grassroots cricket. The ECB recognised that investment in grassroots cricket to create increased participation and interest coupled with a successful England team gives the ECB improved bargaining power when negotiating media rights contracts (together with increased ticket sales) which in turn provides more funding for investment programmes creating a positive financial feedback loop (Figure 1.12).

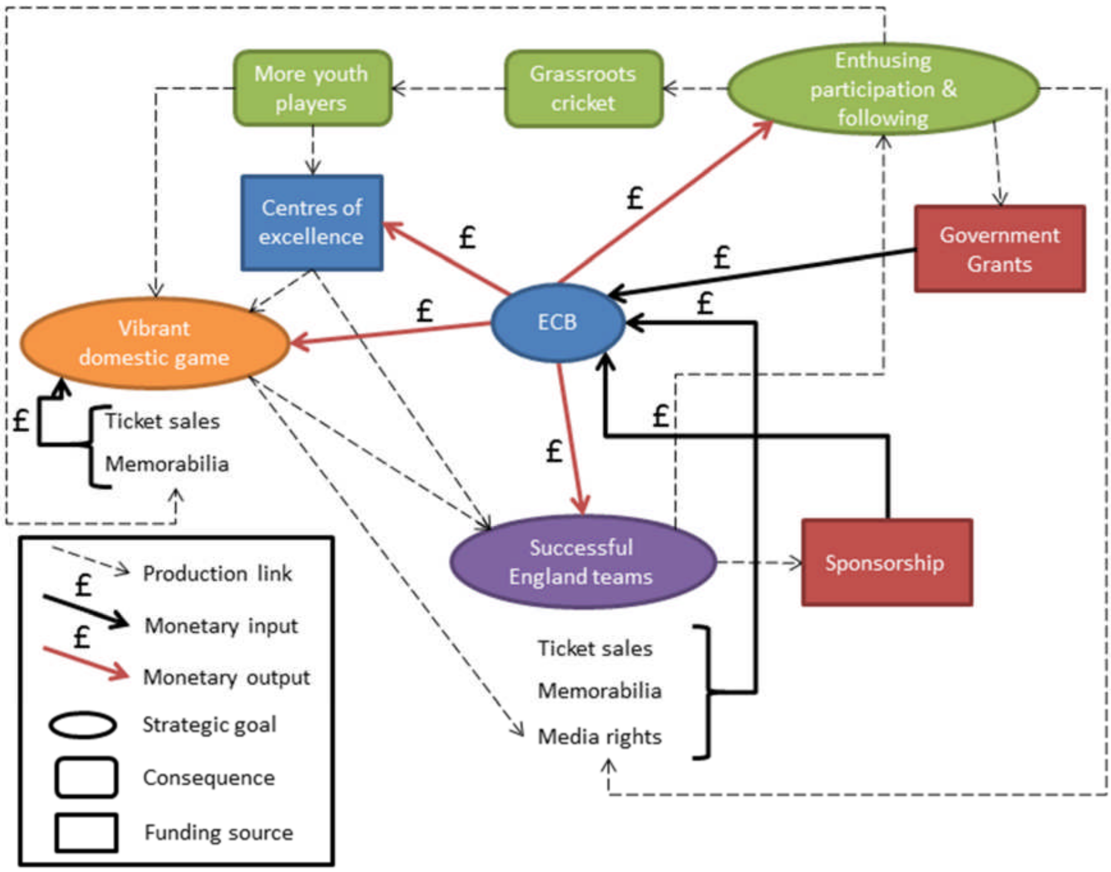


Figure 1.12 Income and expenditure of the ECB in pursuit of its strategic goals and expected consequences creating a positive-feedback loop for increased income.

By investing in grassroots crickets the ECB gains two major advantages, firstly a greater pool of players in the future from which to choose the best talent for county and national teams enabling greater successes and more exciting games further increasing or maintaining public interest. Secondly, it creates a sustainable customer base (particularly if young people are targeted) from which future growth and revenue can be relied upon through demand for media coverage of the sport.

A successful England team also has many advantages. The most obvious is that a successful team attracts greater support leading to increased media coverage demand as well as acting to inspire people into the sport. The national team needs to provide a ‘good’ level of competition in international tournaments so as to provide an exciting viewing experience. This attracts greater audiences, particularly in countries where cricket is hugely popular (such as India), adding value to the media ‘product’ that the national team provides and allowing a higher price to be demanded for it.

Although the County boards and clubs are autonomous, steerage by the ECB is attained by restrictions on funding, unless certain conditions are met. For the County First Class teams this comes in the form of Performance Related Fee Payments (PRFP) where the clubs are rewarded for attaining set goals with increased funds. At club level there is an interest-free loan programme available that can be applied to for funding for certain projects, the ECB can therefore control which project types are funded thus encouraging particular behaviour.

The ‘Building Partnerships’ plan was an undoubted success achieving almost all the goals that they set between 2006 and 2009, notably:

- County spectator attendances recorded a 23% rise
- Expansion in the number of clubs offering women's cricket (49%) and disabilities cricket (137%)
- Creating three England 'superstars' who are recognised by 10% of the population
- Increasing the community coaching provision to more than 24,562 roles (just short of the 25,000 target)
- Establishing a £10m interest free loan programme for community clubs
- Increasing the PFRP proportion of funding for First Class clubs to 34% of total
- Reward scheme for counties providing players for England
- Women's and Disabilities teams in top two in the world
- A 21% investment of ECB income in community programmes

Following the expiry of ‘Building Partnerships’ the ECB released a new strategy agenda entitled ‘Grounds to Play’ (ECB Staff, 2010). ‘Grounds to Play’ kept the same strategic goals as ‘Building Partnerships’ but detailed new objectives to build on the successes of the previous five years.

The success of the ‘Building Partnerships’ agenda has increased participation to the point where many facilities are at maximum capacity, particularly for community and youth programmes. The main driving force of ‘Grounds to Play’ is to address the issue of finding capital funds for investment in developing new and maintaining old facilities. The new plan details expenditure growth for each strategic goal compared to ‘Building Partnerships’ shown in Figure 1.13.

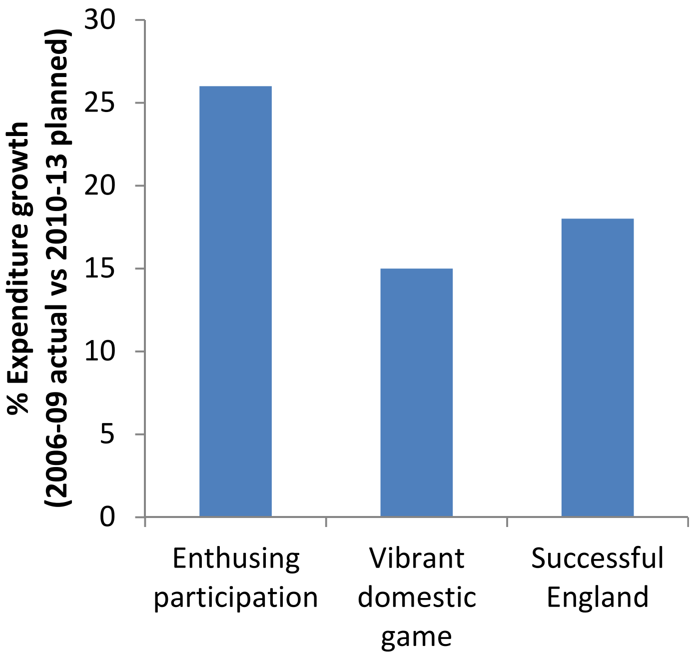


Figure 1.13 Expenditure growth for each strategic goal in ‘Grounds to Play’ compared to actual expenditure from 2006-2009 (ECB Staff, 2010).

The new focus of the ‘Grounds to play’ strategy is highlighted by the increased expenditure dedicated to investment in facilities (Figure 1.14). The shortage of facilities at grassroots level and the need for quality surfaces on which to play is vital to ECB strategy as if the grassroots players turn away because of poor quality or a lack of facilities then the feedback loop in Figure 1.12 is diminished or broken entirely.

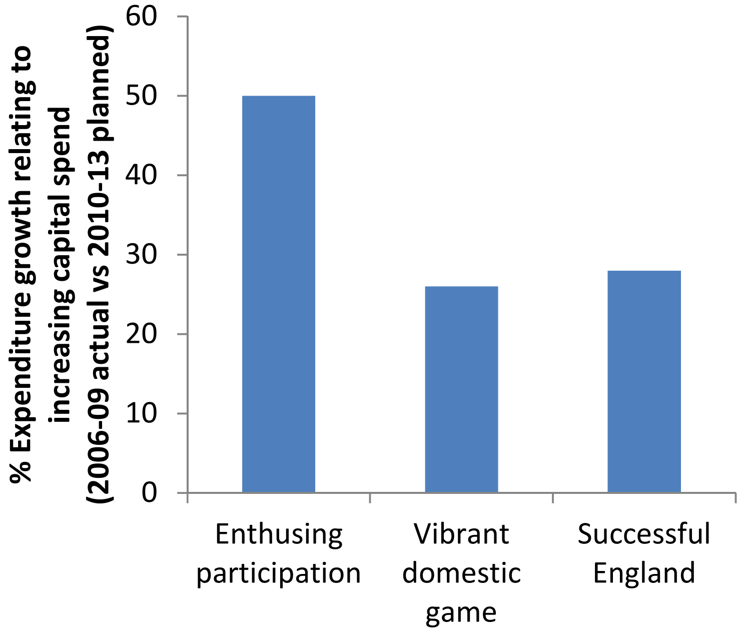


Figure 1.14 Expenditure growth in capital expenditure in 'Grounds to Play' compared to actual expenditure from 2006-2009 (ECB Staff, 2010).

Much of the 'Grounds to Play' objectives are extensions of those in 'Building Partnerships' and the basic premise of the success of the national team and investment in enthusing participation as the primary drivers of sustainable growth is maintained. The new strategy further increases the influence of the ECB over the County teams and clubs established in 'Building Partnerships' with the PRFP and interest-free loan programmes, incentivising the cricket community to fall in line with the ECB agenda.

1.8 Importance of pitches in strategy

The ECB strategy hinges on the success of the national team in the long term and appears to be paying off for the moment at least. National success depends on the skill, talent and dedication of the team players but that can only truly shine on a well-prepared, quality surface. A fact that seems neglected in the strategy agenda of the ECB from 2006-2013. The consequences of a poorly prepared playing service are severe, particularly if it involves the cancellation of a game, resulting in lost income and potentially national embarrassment as was seen in Antigua in 2009 where a test match was almost cancelled and had to be moved to another location as the pitch disintegrated rapidly at the start of the play (Marks, 2009). This would have a severely negative effect on the bargaining power of the ECB when discussing media coverage if the facilities are not up to standard.

The ECB recognises the key role the pitch plays on the Groundsman section of their website, stating ‘For as long as cricket has been played, one of the most important factors responsible for the quality of play is the surface on which the match is played’ (ECB Staff, 2012). A well-prepared cricket surface provides multiple benefits to the value of the media ‘product’ of a cricket match and to the satisfaction ‘value’ of an enjoyable and safe game at lower levels. A well prepared pitch provides consistent bounce and pace allowing batsmen to aim for the ball and equally the bowler can rely on the pitch to deliver the ball where aimed, consequently creating a game based on skill instead of luck from an unpredictable bounce. A predictable bounce gives higher scoring games, which are considered to be more entertaining to spectators and, assuming evenly matched teams, should provide a close contest further increasing the excitement and enjoyment for the spectator increasing the media demand for the ‘product’. At lower levels of the game, particularly for novice players, predictable bounce provides surfaces suitable for developing and exercising their skills enjoyably in a safe environment encouraging players continuing participation.

In first class and international matches lasting several days there is a further requirement for the pitch to degrade at just the right rate to bring the game to a conclusion as time passes. This is intrinsic to the game and is part of the strategy involved in a multi-day match which teams can use to their advantage. If the pitch degrades too quickly the length of the match could be reduced and spectator enjoyment diminished in addition to lost revenue in media and ticket sales thus decreasing the value of the ‘product’.

To create the required quality surface requires a high degree of skill as well as dedicated resources of time and machinery particularly in the changeable climate of the UK. Much of the basis for the manner in which the pitches are treated and prepared is based on historical trial and error, passed on from senior groundsman to trainees, rather than documented, supported scientific evidence and efficacy. This is not to disparage the current practice as much of the treatment applied is correct, but a thorough understanding of the underlying principles of the effect of each treatment helps delineate the optimum time of treatment and when that treatment will turn from a positive effect to a damaging one or a negligible waste of time. An understanding of each technique make for efficient application – this was well illustrated by the ECB funded Optimisation of Cricket Pitch Rolling project (Shipton, 2008) which showed that over 700,000 man hours could be saved and £460,000 of fuel (at 2008 prices) by following the scientifically derived rolling programme compared to current practice. Vitally, the rolling guidelines which were the product of the project were freely available to all groundsmen at every level of the game so that the standard of pitches was raised for everyone.

Following the success of the optimisation of rolling the ECB elected to fund this project to examine aeration.

1.9 Aeration research as part of ECB strategy

Greater recognition in 'Grounds to Play' of the importance of facilities is seen in the increased allocation of funds for their development. The success of 'Building Partnerships' in increasing participation to the point of maximum capacity in many facilities is the primary driving force. As already discussed the quality of the surface is of the utmost importance regardless of skill level. Cricket pitches or netted practise areas are very expensive to build and without proper care will be a very shortlived asset and/or a considerable waste of money. Hence the unmentioned but key component is the skill level of the groundsman in charge.

The ECB has demonstrated a consistent policy of trying to aid the quality of surfaces provided by the provision of subsidised educational resources and advisory services to groundsman at all levels. The ECB has in partnership with the IOG offered a training course on Cricket pitch maintenance containing four parts lasting five days in total, costing approximately £600 per person. Recent innovations have created a new online version of the training course that students can enrol and follow more flexibly hopefully leading to greater uptake as there is now no need to journey to classes or take time from work to do it. The online course provides a cost saving as well (50%), making the course more accessible for those with more limited resources. In addition to this a number of advisory booklets are freely available such as the ‘Guidelines for rolling in cricket’ (James and Shipton, 2009) and the ‘Recommended guidelines for the construction, preparation and maintenance of cricket pitches at all levels of the game’ (ECB Staff, 2011), as well as ‘Natwest Pitch Doctor’ which provides a series of short instructional videos on various cricket groundsmanship topics.

The ECB pitch advisors scheme provides for a modest fee (£75-250, depending on level of service required) a trained advisor whose role is to provide guidance to groundsman on issues of pitch performance, assess pitch performance and help to guide clubs and groundsman in the development of facilities particularly on large or risky projects and procedures of which there is a lack of experience in the club. The guiding principle is to take experience in groundsmanship from the top professionals and bring it to the recreational/non-professional. The ECB pitch advisers scheme is set to expand under ‘Grounds to Play’ as well as various funds being made available to help clubs in addressing areas of pitch quality.

The rolling guidelines demonstrated the huge benefits that can be gained from applying the scientific method to optimising and understanding groundsmanship strategies and channels exist for transferring that knowledge from elite professional to volunteer level, but first the information must be gathered and its implications explored to which end further resources must be applied.

The gains for the ECB from the aeration research project are illustrated in a benefits network (Figure 1.15). The project is designed to output a set of guidelines, similar to the optimisation of rolling to give guidance to the groundsman at all levels of the game based on clear, demonstrable effects of aeration in cricket soils.

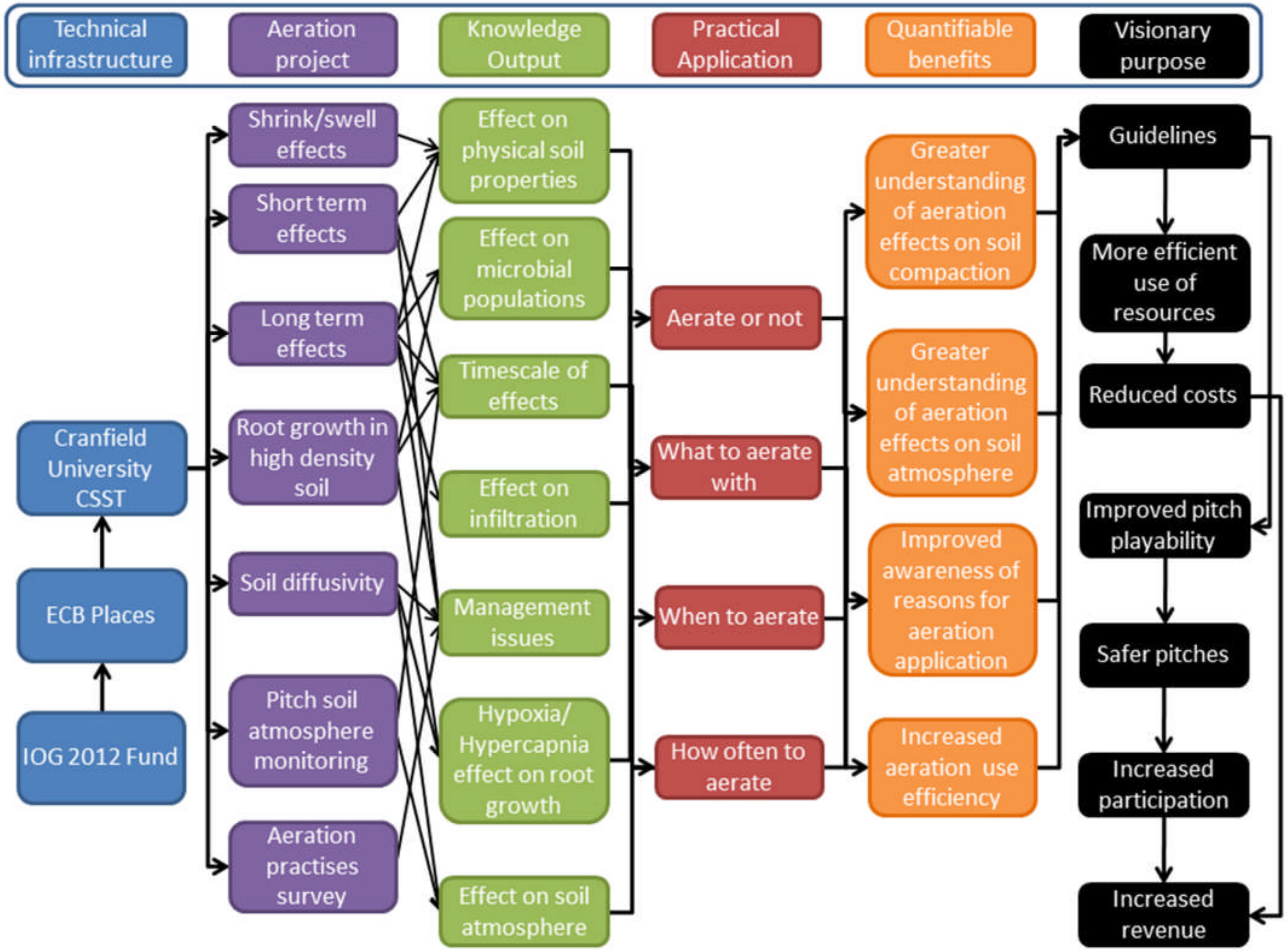


Figure 1.15 Benefits network of the aeration research project for the ECB.

Clear guidance on the necessity of applying aeration and its effects will provide a basis for improved pitch quality thereby aiding the strategic goal of increased participation. Additionally the guidelines will ensure the efficient application of aeration to prevent the unnecessary or pointless applications, thereby saving precious resources that can be returned to the club.

The success of the national team is the key component of the ECB strategy together with increasing participation and following of the sport to provide increased revenue for reinvestment in the game. This strategy has been a proven success since its introduction in 2006. Groundsmanship and pitch quality have always been a concern of the ECB and steps have been taken to provide information channels and funding for groundsman to improve the overall quality of the surfaces they prepare. In order to make proper use of the system however, it must be insured that the information being passed is of good quality and useful to the groundsman at all levels of the game. The success of the rolling guidelines show the benefits that can be gained from research projects like this. The increasing use of facilities as the popularity of cricket increases places extra burdens on the pitch and it is therefore of increasing importance that the best possible advice is given to groundsman on how to maintain them.

A good game of cricket cannot be played on a poorly prepared surface, the game is so crucially linked to the surface, the two are inseparable. A good quality surface is most efficiently and easily attained by a solid understanding of the dynamic processes at work within and upon the soil and the effect of the groundsmans activities upon them.

Clearly, pitch quality is crucially important to the long term goals of the ECB and the aeration research forms an integral part of this.

1.10 Thesis Structure

Chapter 1 Introduction:

Chapter 1 discusses the background to the project particularly the role of aeration in general autumn maintenance and intended outcomes of aeration. An overview of the forms of aeration currently in general use and the current guidelines are discussed. The discussion then moves on to describe the overall strategy of the sponsor and how the project sits within their business goals.

Chapter 2 Literature Review framing the creation of the aims and objectives of the research project:

The basic theory supporting the later experimental work is reviewed and discussed in this chapter, along with the implications it has on experimental design. Each chapter describing the method and results of an experimental method contains an additional discussion of the related specific theory.

Chapter 3 Current aeration practices:

Current aeration practice was investigated through a survey of cricket groundsmen to assess the variation in application and views throughout the industry. The analysis was broken down by facility type and the differences between discussed in light of different treatments applied, diverse viewpoints on aeration and the prevalence of root breaks and layering within UK pitches.

Chapter 4 Soil Shrink-Swell:

The soils used in cricket pitches in the UK can have up to 35% clay and exhibit significant shrink and swell behaviour. The shrink and swell of the soil is a natural process by which compaction is reduced. Two new methods based on time-lapse photography were used to examine the shrink and swell properties of five diverse soils and the possible implications this has on the necessity and effectiveness of aeration discussed.

Chapter 5 Laboratory Scale Examination of Diffusion in Soil:

Aeration by its name implies an increase in air supply to the soil, specifically the roots and is one of the primary claims of the benefits of aeration. A new method for analysing the rate of oxygen diffusion into a compacted clay loam was developed and used to compare the rate of oxygen diffusion of aerated and unaerated soil in the laboratory.

Chapter 6 Effect of bulk density and solid tine aeration on root growth and microbial biomass:

Increasing bulk density has been linked to shallow rooting and reduced shoot growth. Three bulk densities were assessed for their effect on the shoot and root growth of the grass plant together with a measurement of microbial populations. Sealed and unsealed pots were used to examine the potential effects of restricted gas exchange. Aerated and unaerated treatments were used to examine what benefits were conferred, if any, in terms of root growth and microbial populations.

Chapter 7 Field Trials of Equipment:

The culmination of a 28 month study examining the effect of five different aeration treatments on two soils at a field site manufactured and maintained to mimic a real cricket pitch. The study examined the immediate and long term effects of the treatments on the physical and biological properties of the soil particularly in relation to seasonal changes in weather conditions and their effect on the soil through natural shrink-swell and freeze-thaw processes.

Chapter 8 Effect of aeration on the soil atmosphere in the field:

Chapter 5 examined bare soil units in a controlled laboratory environment. This knowledge was taken into the field for assessment using specially designed and constructed equipment installed in a set of cricket pitches. The soil atmosphere within two pitches was examined for the effects of aeration over a year long period on the concentrations of the constituent gases. The experiment aimed to determine whether the observed effects in the laboratory were manifested in the field with the addition of the grass plant and changing climatic conditions.

Chapter 9 Research Synthesis & Interim Guidelines:

The results of each experiment are summarised and discussed in light of the possible interactive effects between factors on the effectiveness of aeration in cricket pitch soils and the subsequent effects on management practice as a consequence. An appraisal of the contributions to knowledge, research limitations and suggested future work is included. The key points from the research were extracted and a set of interim guidelines developed with a clearly defined role and application for aeration in cricket pitch soils together with a decision pathway for choosing the best treatments to tackle specific pitch problems. The structure of the cricket groundsman community from village green to first class is discussed and the implications for this on the uptake and acceptance of the guidelines is discussed. Strategy for accelerating the assimilation of the aeration guidelines is discussed and the possible communication channels that can be used to facilitate this.

Chapter 10 Conclusions:

The chapter aligns the project objectives with the thesis conclusions and lists the publications achieved to date.

2 Literature Review framing the creation of the aims and objectives of the research project

No direct research on the effectiveness of aeration in cricket pitches was found. Most aeration research is carried out on golf courses in the USA and naturally focuses on sand based constructions that predominate in this industry. The applicability of this research to the behaviour in the clay-based soils of cricket pitches is limited but provides a reference for the potential effects in cricket pitches. Other research examining the underlying principles regarding the compaction of soil and the behaviour of gas and water transport through the profile has been studied extensively and whilst not exclusively developed for cricket pitches is equally applicable and will be examined here. Gaps in the knowledge are identified and key research questions and objectives formed. The literature review presented here is to provide the foundation for the key principles behind the research and the gaps therein, for each experiment a more detailed examination of the literature pertaining directly to it is presented in the relevant chapter. This is done to provide the reader with the details required to reference and understand each chapter directly without the need to continuously refer to previous sections and recall experiment specific details throughout.

2.1 The grass plant and cricket pitches

The grass plant forms an essential component of a cricket pitch. The root system is essential for removing water from the pitch whilst the shoot growth influences the ball-surface interactions during the game. Water removal is necessary for drying the pitch out to cause soil shrinkage to get the high bulk densities needed (Baker *et al.*, 1998b; Adams *et al.*, 2001). Ultimately the plant is not being grown to achieve a high yield but a strong and healthy plant is still required to fulfil its functions, particularly water removal, as effectively as possible. Supporting the growth of a healthy grass plant in a dry, high bulk density rootzone is what makes cricket pitches challenging for groundsmen.

A deep root system has three main benefits; it increases the depth of drying, improves the binding strength of the soil and makes available a greater nutrient pool to the plant. An increased nutrient pool provides greater resilience to the plant, particularly against drought. It is generally recommended that root depth be 100 mm or greater into the profile. The effect of the roller is predominantly in the top 75 mm and diminishes below 100 mm (Shipton, 2008). Ball surface interaction is unlikely to be affected by soil factors below 75-100 mm depth therefore 100 mm is the minimum requirement.

Reduced root mass and root penetration will negatively affect the extent of water removal which will in turn affect the playability of the pitch. In a compacted soil this is not an easy task. Root growth and distribution are altered by compaction in soils (van Ouwerkerk and van Noordwijk, 1991). Different crops show different sensitivities to compaction. Dexter (1986) reported the root growth of monocotyledons was reduced with increasing compaction with a maximum recommended limit of 3 MPa penetration resistance. Chan *et al.* (2006) found no difference between a wheat crop grown in soil >2 MPa resistance to one grown in 1 MPa. Dicotyledons were found to be far less tolerant of compacted soils with 0.4 MPa as an upper limit (Dexter, 1986). Shipton (2008) calculated using the penetration resistance model of Dexter *et al.* (2007) that a clay loam of 30% clay content would exceed 3 MPa penetration resistance at a bulk density of 1.75 g cm^{-3} at 10 kPa tension and as such is within the realm of bulk densities reported in cricket pitches. Shipton (2008) and McGowan *et al.* (2008) found increasing bulk density caused increased root mass nearer the surface and a decline in root mass further down the profile.

The root network also plays an important role in controlling crack formation as the pitch dries. Roots have been shown to positively increase soil strength. Tengbeh (1993) and Adams *et al.* (2005) found the grass roots ‘considerably’ increased shear resistance, Van Wijk (1984) found grass roots contributed 0.8-1.6 MPa to the penetration resistance of soils. It is not just the physical strength of roots that adds to the strength of the soil but also the exudates which enhance root soil connections (Dexter, 1991; Huang, 2000). The cracks are not themselves the cause of inconsistent bounce so long as the edges of the cracks do not crumble (Adams *et al.*, 1994). Adams *et al.* (2004) states that inconsistent bounce is due to horizontal breaks (often known as 'root breaks'). One way of creating horizontal breaks is by improper rolling when the soil is too wet as it increases horizontal movement of the soil (James and Shipton, 2009). Layering can also be caused by incompatible topdressing; if the applied loam has shrink-swell properties different from the underlying soil then expansion and contraction will occur at different rates and bonding between the two soils will be stressed or broken, as such the compatibility of topdressing is paramount (Adams *et al.*, 1994; ECB Staff, 2011). Bonding of the topdressing to the underlying soil occurs via physical-chemical processes and biological processes. The physical-chemical process generally involves the formation of bonds between mutually attractive surfaces (Brady and Weil, 2001). Organic matter in the soil provides a nutrient source for microbial population and the breakdown of this material as well as exudates from the organisms themselves provide gels, polysaccharides and long-chain organic molecules that act like glue to hold particles together. In addition fungal hyphae and roots grow through and bind the soil together further strengthening it. If one soil expands much more rapidly than another the bonds spanning the boundary between the two soils will be stressed or broken as the distance between the connected particles or aggregates increases. Whilst organic matter can help increase the binding strength of the soil a large amount of coarse, non-decomposed organic matter in or on top of the soil when the topdressing is applied will significantly reduce the binding strength between the soils (Adams *et al.*, 1994; Brady and Weil, 2001) increasing the chance of forming a break as well as forming an energy absorbent layer reducing rebound energy of the ball causing dull and lifeless pitches. The role of roots in increasing soil strength has been attempted to be exploited by using the hollow tine and deep drill aeration techniques to create channels for root growth deeper into the profile using the strength of the roots to hold the pitch together and reduce the effects of layering (Woods, 2012). The efficacy of this technique has not been robustly analysed and the evidence remains purely anecdotal.

Whilst the grass plant brings many benefits it also has a substantial drawback, and this is the build-up of organic matter in the soil, and specifically the development of thatch. It has been reported that soils with higher organic matter content have lower bulk densities and greater water content after simulated match preparation (Baker and Adams, 2001; Baker *et al.*, 1998b; Baker *et al.*, 1998c) thus reducing the playability of pitches. Soil organic matter affects many soil properties but particularly soil structure and consequently water holding capacity. Soil organic matter incorporates living, non-living organisms and humus (products of organic origins that are no longer identifiable as tissue). The breakdown of humus can be approximately split into two categories, the production of humic and non-humic substances. Non-humic substances, such as polysaccharides, act as glues to help bind the soil particles together encouraging an aggregate structure. Humic substances reduce the plasticity, cohesion and stickiness of clay soils aiding the formation of granular loose soils (Brady and Weil, 2001) - in conventional farming high organic matter is generally viewed as beneficial in creating a good seedbed for this very reason. In a cricket pitch a granular loose structure is the very opposite of the aimed intent. High organic matter content, especially large, non-decomposed material, has been negatively correlated with soil binding strength (Adams *et al.*, 1994) particularly fibrous organic matter forming soft spongy layers. These soft sponge-like layers resist compaction from the roller (Shipton, 2008) (as they are easily compressed but highly elastic), retain water (due to increased porosity) and reduce soil stiffness (because of their elasticity), negatively effecting ball bounce (Adams *et al.*, 1994). (Baker *et al.*, 2003a) categorised values of organic matter, water content, and bulk density in pitches at four depths in the profile and attempted to correlate the findings with umpires reports on ball bounce (Baker *et al.*, 2003b). Correlation between reduction in ball bounce with greater organic matter content, greater water content and reduced bulk density was good for depths below 20 mm. Above 20 mm the correlation appeared to be reversed with high bulk density, reduced organic matter content and reduced water content corresponding to reduced ball bounce. The two possible explanations put forward were either the umpires reports were biased due to the ability to observe the soil surface elastic properties or that increased surface deformation resulted in higher ball trajectories.

Thatch is layers of organic fibrous material found in turf and forms as the rate of accumulation exceeds the rate of decay. Excessive thatch has been found to cause reduced hydraulic conductivity (Baker *et al.*, 1995), decreased infiltration (Murray and Juska, 1977), reduced tolerance to cold temperatures, as well as increased disease and insect problems (McCarty *et al.*, 2007). Thatch often manifests as a soft spongy layer on the surface of the soil, causing a reduction in bounce and pace as well as reducing the binding strength of the soil for any applied topdressing (Adams *et al.*, 1994). Factors attributed to causing the build-up of thatch include particular vigorous-growing cultivars, poor soil gas exchange and excessive use of nitrogen fertilisers. Methods for the control of thatch include reduced use of pesticides, reduced fertilizer use and improved soil gas exchange (Brown, 2005). These measures are all primarily aimed at increasing the microbial breakdown of thatch. Alternative methods include hollow core aeration (Adams *et al.*, 1994; Rieke and Murphy, 1989; Brown, 2005; Murphy *et al.*, 1993) and the physical removal via scarification (Adams *et al.*, 1994; ECB Staff, 2011; Brown, 2005). As discussed in Section 1, hollow core aeration is not generally effective on cricket pitches, leaving only scarification (and similar treatments, such as linear aeration) and aiding the microbial decay of thatch as the only options for control. As aeration is aimed at ameliorating the negative effects of soil compaction it would be expected to aid the microbial decay of organic matter but no research could be found that has examined this.

2.2 Importance of the soil atmosphere and gas exchange

The composition of the free atmosphere is approximately 78% nitrogen, 21% oxygen, 0.04% carbon dioxide with the remainder composed of various trace gases. The composition of soil air generally has <21% oxygen and >0.04% carbon dioxide (Stępniewski and Gliński, 1985). Soil air composition is influenced by the rate of consumption and emission of gasses within the soil by both chemical and biological processes, and the physical transport of gases between the emission or consumption sites and the free atmosphere (Simojoki *et al.*, 1991). Previous research has found a very large variation in oxygen concentration in the soil atmosphere, ranging from 20% oxygen in a well aerated soil to less than 1% in a flooded soil (Stępniewski and Gliński, 1985; Good and Patrick, 1987; Smit and Stachowiak, 1989; Nobel and Palta, 1989). Similarly carbon dioxide concentrations vary (because oxygen cannot enter the soil, carbon dioxide will likewise be restricted from leaving) and have been reported between 0.1% in a clay loam without plant roots (Nakayama and Kimball, 1988) and within the rooting zone of plants typical around 1% (Good and Patrick, 1987; Nakayama and Kimball, 1988; Kucera and Kirkham, 1971) but as high as 5% in some clay soils (Jeffrey, 1987). The concentration of both gases varies throughout the profile increasing in proximity to the source, e.g. the roots for carbon dioxide and the surface for oxygen (Stępniewski and Gliński, 1985).

Gas transport in the soil profile occurs via two processes, mass flow and diffusion. Mass flow is caused by pressure differences between regions creating a flow of material to equalise the discrepancy (Jury and Horton, 2004). Mass flow in the soil can be induced by atmospheric pressure changes from weather fronts, temperature changes and wind. The causes of mass flow are intermittent and the effect dampened with increasing depth due to the flow restrictions imposed by the soil, through narrow pore sizes and the creation of eddy currents, rather like placing a wall of solid foam of increasing thickness in front of a fan, eventually the flow of air from the fan is essentially reduced to zero. Gas diffusion occurs down a concentration gradient. In soil the respiration process of the plant roots and soil flora and fauna creates a concentration gradient that is constantly active without the need for external causes as in mass flow. Due to the dampening effect of the soil on mass flow and its intermittent nature, gas transport occurs primarily by diffusion through the soil pore network (Stępniewski *et al.*, 1994; Marshall *et al.*, 1996; Stępniewski and Gliński, 1985; Moldrup *et al.*, 2001). Some plants, e.g. rice, have adapted to be able to exchange gases between the free atmosphere and their roots through the plant tissue, however, most plants depend on transport through the soil pores (Marshall *et al.*, 1996).

The primary gases observed in the soil atmosphere and their associated consumption and production processes are listed in Figure 2.1.

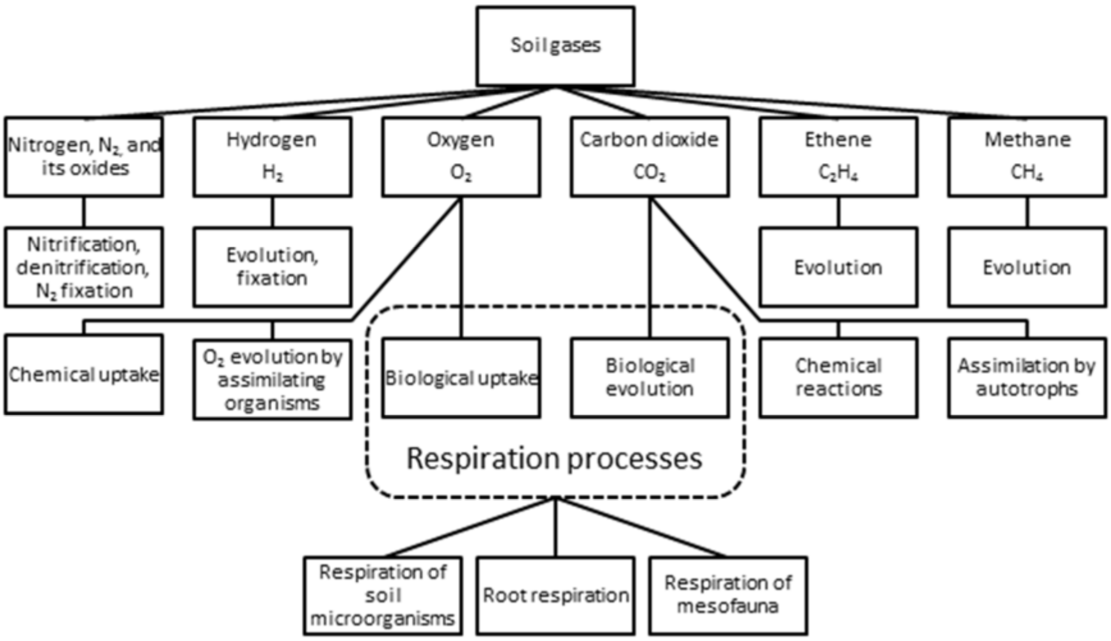


Figure 2.1 Scheme of soil gases and their associated consumption and production processes from (Stępniewski and Gliński, 1985).

The most prevalent of these are oxygen and carbon dioxide (Stępniewski and Gliński, 1985). Oxygen is consumed and carbon dioxide released by aerobic respiration (carbon dioxide is also released via anaerobic respiration without any oxygen intake) within plant roots, soil microbes, microfauna (<0.1 mm in size), mesofauna (0.1-2 mm in size) and macrofauna (>2 mm in size), the most important of which are the plant roots and soil microbes. The respiration rate is not constant and depends on numerous factors, including temperature, water content, organic matter content, oxygen concentration, carbon dioxide concentration, soil structure, soil pH, as well as chemical inputs such as fertilizer and pesticides. Table 2.1 shows the effect of temperature and compares bare soil (i.e. no plant roots) with cropped soil (with plant roots). Low temperatures clearly reduce both plant and microbial respiration.

Table 2.1 Oxygen demand and carbon dioxide release of soil at two different temperatures, one cropped with kale and the other left bare (Currie, 1970).

Soil temperature at 30 cm	17 °C		3 °C	
Treatment	Cropped	Uncropped	Cropped	Uncropped
Oxygen demand (l m^{-3} day^{-1})	16.6	8.1	1.4	0.5
Carbon dioxide release (l m^{-3} day^{-1})	17.4	8	1.5	0.6

Plant roots whilst representing only a small fraction of soil mass respire much more intensively than the soil microbes forming threads of high oxygen demand through the soil (Stępniewski and Gliński, 1985). Oxygen is the terminal electron acceptor in the mitochondrial electron transfer chain and is therefore essential to the roots as this represents the primary source of energy for them as well as many other soil microbes. The reduction of oxygen to below critical levels is termed hypoxia and occurs when the respiratory activity exceeds oxygen availability (Fukao and Bailey-Serres, 2004). The critical level of oxygen concentration varies from plant to plant and in different environmental conditions; this is clearly evident seen in Table 2.1 where the oxygen demand at 3 °C is markedly less than that at 17 °C.

There is little research into the effects of hypoxia on turf grass directly. Agnew and Carrow (1985) found that a low oxygen environment increased root porosity in Kentucky bluegrass (*Poa pratensis*) and lowered rooting depth in plants that did not respond with increased porosity as well as reducing water uptake. Morgan *et al*, (1965) also reported reduced rooting under low oxygen conditions in turf but did not report the species. Considerable research exists for the more general effects in other plants. As mentioned before some plants, particularly wetland species, have adapted to transfer oxygen through plant tissues and can survive complete submergence. The tolerance of other species varies and depends on the adaption capabilities available to them. Long term adaption to low oxygen root environments usually involve physiological adaptions to increase intra-tissue oxygen transfer through the plant, such as the development of aerenchyma (Fukao and Bailey-Serres, 2004; Drew *et al.*, 2000). The plant can adapt to short term deprivation by adjusting the cellular metabolism to temporarily conduct anaerobic metabolism of pyruvate by glycolysis. Anaerobic metabolism releases far less energy than aerobic respiration. Consequently anaerobic respiration will consume the carbohydrate stores of the plant at a considerably higher rate and the extent of these stores is thought to be one determining factor in survival (Fukao and Bailey-Serres, 2004). Even if the plant is not killed by the low oxygen environment considerable damage can still be done due to the production of toxic substances such as acetaldehyde and ethanol causing cell death and chlorosis (Huang and Scott Nesmith, 1999).

Carbon dioxide is also toxic in sufficient quantity and has been shown to reduce water absorption (Kramer, 1940; Chang and Loomis, 1945). Bunnell *et al.* (2002) found a carbon dioxide concentration of 2.5% reduced root length and density for creeping bentgrass (*Agrostis stolinifera*) and that 10% had a deleterious effect on above ground turf quality. Williamson (1968) found 6% carbon dioxide was toxic to broad beans (*Vicia faba*). The toxic effect is thought to relate to the formation of a low pH inside the cell cytoplasm from the formation of carbonic acid from dissolved carbon dioxide (Bunnell *et al.*, 2002).

For continued aerobic respiration the oxygen within the soil needs to be replaced and the carbon dioxide produced needs to be removed (Hillel, 2004). This is vital to maintain a healthy grass plant and a healthy grass plant is vital to maintaining a good quality cricket pitch (Section 1). One of the principal causes of a low oxygen environment is wet soils (Sairam *et al.*, 2008) which is exacerbated when the soil is compacted due to the reduced pore volume and inter-connectivity (Stępniewski *et al.*, 1994). Whilst the climate across the British Isles does vary considerably it can generally be relied upon to be wet over the autumn-winter period. Groundsmen will irrigate over the drier summer period including as part of match preparation. Cricket pitches are deliberately compacted so when combined with irrigation and rainfall, supplies the requisite conditions for a hypoxic root environment. It is the interaction of soil water and soil structure that is most influential upon the soil atmosphere and the capability for effective gas exchange (Stępniewski and Gliński, 1985). Considerable scope exists for the examination of the effect of compaction on turf in clay loams and specifically the role of gas exchange which has come under little scrutiny, particularly regarding the effect of mechanical aeration techniques upon it.

2.3 Soil structure and the pore network

The soil structure is defined as the manner in which the soil particles are aggregated together. Soil structure greatly influences the water movement, heat transfer and aeration status by determining porosity of the soils. It is the nature of the pores in the soil, their width, length, and connectivity that affects these processes (Brady and Weil, 2001). The pore network consists of a web of channels spread throughout the soil of various sizes. Marshall *et al.* (1996) classifies the pores into four categories according to size (Table 2.2).

Table 2.2 Pore size categories and description of properties. Adapted from Marshall *et al.* (1996).

Size	Description	Water relation
10 mm to 1 mm	Fissures, tunnels and spaces between clods	Transmit water freely but only if the soil is flooded
>1 mm to 30 µm	Pores between aggregates and within them or pores between particles in sandy soils	Drained at field capacity but transmit water during infiltration
>30 µm to 200 nm	Mainly pores within aggregates	Water retained in these pores is available for plants
>200 nm to 1 nm	Pores of the clay complexes. Primarily responsible for shrink and swell properties.	Pores change in size with water content

The pore network is responsible for the transport of both liquids and gases in the soil. Generally the greater the pore size the more effective it is at transporting both gases and liquids.

The transport of water through the pore network is dependent on pore size for two reasons, matric potential and flow restrictions. The matric potential of a soil is created by adsorption of water on the surface of the soil particles and from capillarity. The matric potential determines the amount of water that is retained within the pore network against gravity (partly determining field capacity) and against specific suctions as applied via plant roots for example. The smaller the pore size, the greater the matric potential and the greater the suction is required to withdraw the water from that pore (Jury and Horton, 2004).

Gas diffusion through soils has been studied extensively in both natural and agricultural systems (Stępniewski *et al.*, 1994; Stępniewski and Gliński, 1985; DeSutter *et al.*, 2008a; Kavanagh and Jelley, 1981; Lange *et al.*, 2009), however little attention has been played to the role of the soil atmosphere in the health and functionality of sports turf. Air filled porosity can be used as the most basic indicator of soil aeration. This parameter, coupled with values of total porosity and soil matric potential, has been used in previous studies to give general guidelines in agricultural systems as to what soil characteristics represent an appropriate level of aeration for optimal crop production with a general recommendation of around 10% air-filled porosity as a minimum (Stępniewski *et al.*, 1994; Stępniewski and Gliński, 1985; Grable, 1971).

In agricultural systems air filled porosity is increased through destructive mechanical techniques, such as inversion ploughing (Stępniewski *et al.*, 1994). However, in a sports surface context, it is important that the level of the playing surface is not adversely affected by the aeration technique, as this will affect the playability of the pitch. Therefore a distinction must be made between decompaction and aeration. Decompaction increases total soil porosity by raising the level of the soil surface thereby decreasing its bulk density. In cricket pitch maintenance this is not a practicable option and is not considered as an aeration technique. Aeration attempts to alleviate the effects of soil compaction and facilitate gas exchange and encourage deeper root growth through the soil profile by the creation of artificial macropores with minimal surface disruption (Adams *et al.*, 1994; Nektarios *et al.*, 2004).

The interactions of different parameters in the soil affecting the diffusion of gases within it are extremely complicated and highly interlinked (Figure 2.2).

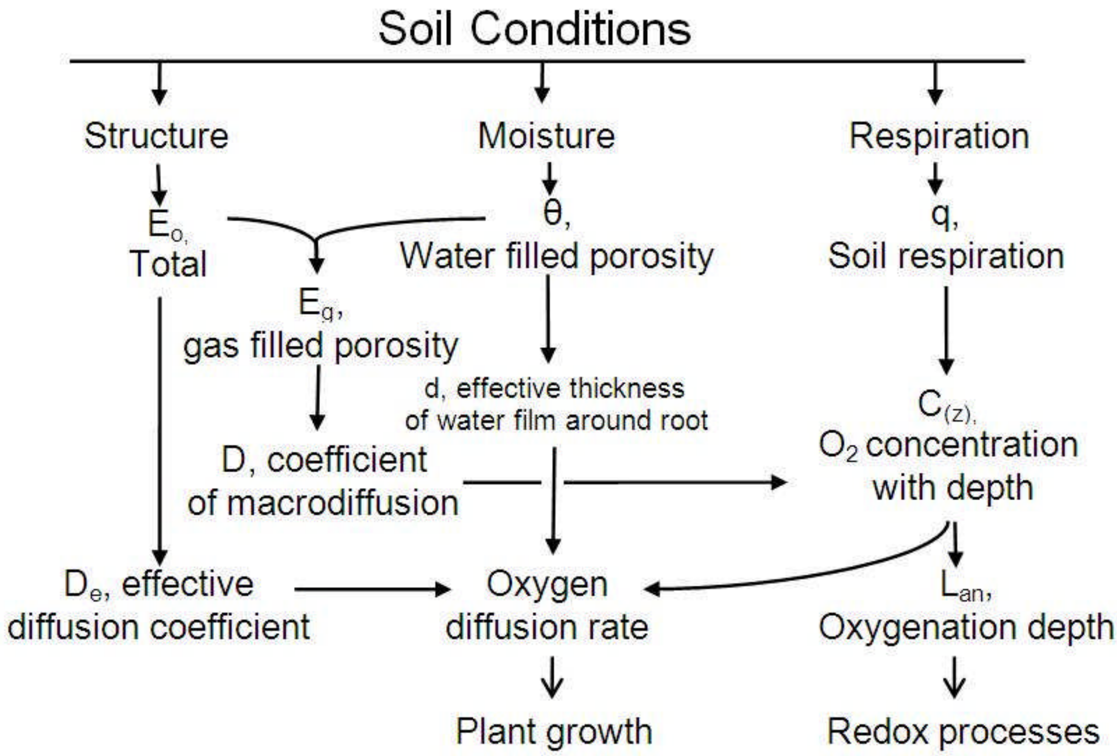


Figure 2.2 Schematic diagram showing the interactions between critical parameters in determining gas diffusion through soils, adapted from Stępniewski and Gliński (1985).

The principal path for gas exchange in soils is by diffusion down a concentration gradient (Stępniewski and Gliński, 1985). The diffusivity of the gases depends on temperature, air-filled porosity and the pore networks continuity and tortuosity. Continuity describes the level of interconnectivity between pores and the number of 'dead-ends' and isolated pores. Tortuosity refers to the absolute distance required to travel between two points within the soil through the pore network relative to the straight line distance (Ball *et al.*, 1988). The micro structure and water potential of the soil have considerable impact on these factors. Small pore radii restrict the mass flow of water, decreasing hydraulic conductivity, and create high matric water potential, reducing the difference between saturation point, field capacity and permanent wilting point of the soil. Increased water retention and small pore radii also results in blockages of pore entrances by water films as gas diffusion through water is approximately 10,000 times slower than through air (Marshall *et al.*, 1996). This leads to a decrease in connectivity and creates anoxic zones within the soil by sealing areas of the pore network from gaseous exchange. This increases the concentration of potentially toxic waste products resulting from respiration and other metabolic activity.

By creating macropores through aeration of the soil the connectivity of the pore network is increased, reducing the distance for gas exchange between the soil and atmospheric air and thus increasing the oxygen supply to greater depths of soil.

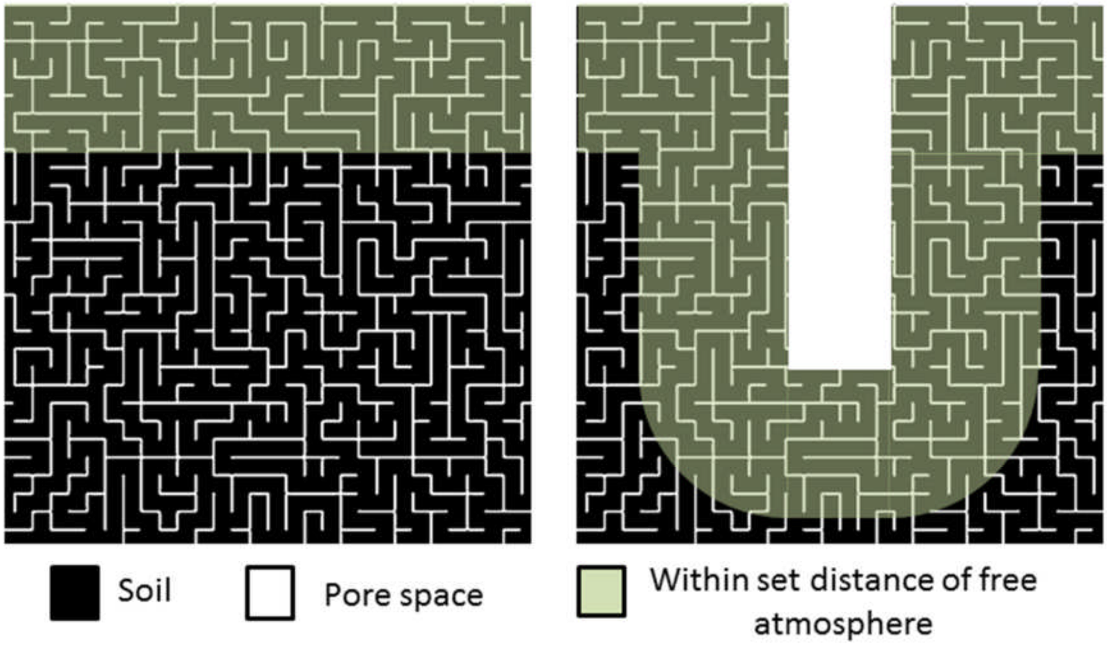


Figure 2.3 Diagram illustrating a hypothetical soil structure (left) and the effect of adding an artificial macropore (right) in reducing the distance for gas exchange with the free atmosphere.

This has several beneficial effects including:

- increased oxygen concentrations at depth, allowing greater root respiration, and improved root survival at greater depths (Stępniewski and Gliński, 1985).;
- aiding the microbial breakdown of organic matter in the soil and reducing the formation of thatch (Rieke and Murphy, 1989).

The complicated relationships between, and the large number of factors affecting the soil atmosphere make it impossible to quantify the effectiveness of any aeration treatment using just one factor (Stępniewski and Gliński, 1985). It is suggested that a more holistic approach by the measurement of multiple parameters would provide a more balanced and effective measure of soil aeration status. There are a number of different indices of aeration status that have been used in attempts to define soil aeration and quantify its effects on other soil parameters and plant health. Air filled porosity (Grable, 1971); oxygen concentration in soil air (Meyer and Barrs, 1991; Armstrong and Gaynard, 1976); and oxygen diffusion rate (Letey and Stolzy, 1967; Blackwell, 1983) have all been proposed. In a sports surface system the highest resolution determinant, generating the most suitable data to inform management strategies is to monitor soil oxygen concentrations. Other gas concentrations, such as carbon dioxide and trace gases from biological processes, can also be monitored in parallel. The presence of trace gases such as CH_4, H_2S, N_2O, C_2H_4 and H_2 are an indication of poor aeration even at low concentrations (Stolzy *et al.*, 1981). Indices such as water content, dry bulk density and soil porosity help relate the soil structure to soil gas exchange. Soil microbial structure and biomass together with root depth, provide a measure of the respiratory elements of the interchange. The wealth of information provided by these measurements should provide a viable basis to quantify and critically assess the aeration status of the soil and the effectiveness of any aeration treatments applied to it.

2.4 Soil compaction

Compaction occurs via the application of a force to instigate the closer packing of soil particles. This closer packing is only made possible by a decrease in pore space between soil particles and the expulsion of air, giving an overall smaller volume and consequently a higher density (Whitlow, 2001). Soil compaction drastically effects the distribution of pore sizes (Figure 2.4) resulting in a reduction in the number of macropores and a subsequent increase in micropores (Marshall *et al.*, 1996; Jury and Horton, 2004).

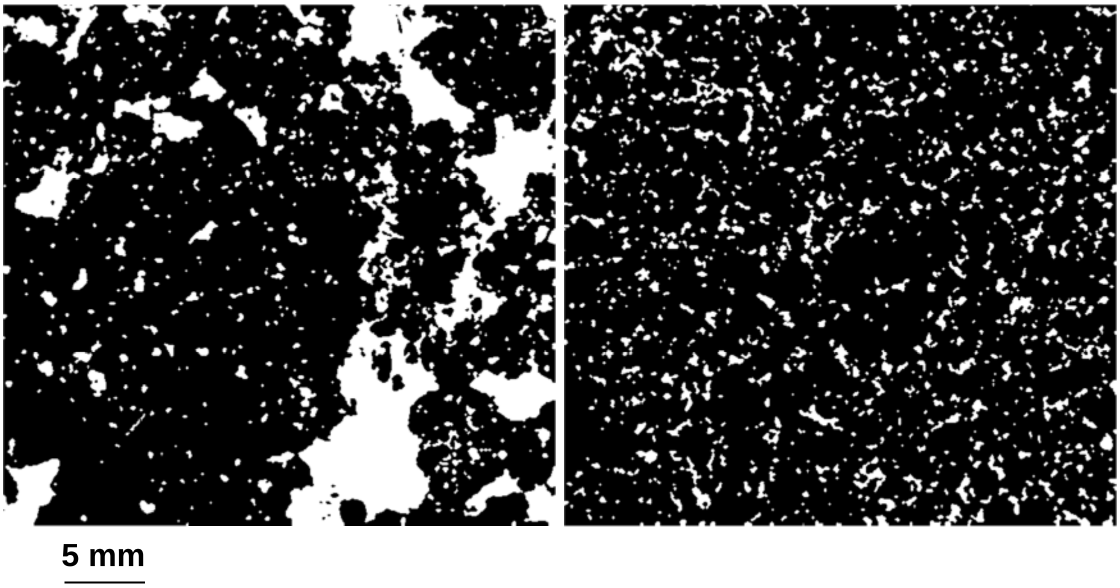


Figure 2.4 Binary image pore maps from thin soil sections at two different bulk densities (Harris *et al.*, 2003): 1.2 g cm^{-3} (left) and 1.6 g cm^{-3} (right). White indicates pore space, black indicates soil particles.

Cricket pitches are deliberately compacted using a smooth wheeled roller to provide a hard, consolidated surface to reduce absorption of the energy of the ball on rebound with the surface (Shipton, 2008). The compaction of the soil vastly reduces the soils capacity to transport both air and water. Both the diffusivity of the gas and transmission of water are dependent on soil porosity and the pore networks continuity and tortuosity. The smaller pore radii increase the matric potential and reduce the difference between saturation point, field capacity and permanent wilting point, potentially decreasing available water to the plant and increasing its vulnerability to stress and disease. Compacted soils present difficult growing conditions for the grass plant resulting in decreased root biomass (McGowan *et al.*, 2008), reduced root growth and increased difficulty in the uptake of both water and nutrients (Waddington and Baker, 1965; Boone and Veen, 1994). Soil compaction in clay soils is closely linked to an increase in soil strength, this increased soil strength has been implicated as a factor in restricting plant root growth by mechanical impedance (Stępniewski and Gliński, 1985). Recent work has shown that for turfgrass mechanical impedance may not be an overriding reason for poor root growth, Shipton

(2008) found that total root mass was not decreased due to compaction but the root density became more concentrated towards the shallower regions of the profile.

It is apparent that compaction in soils negatively affects root penetration and growth and yet cricket pitch preparation to achieve high bulk densities requires compaction of the soil as well as a deep, widespread root system for water extraction and reduced crack formation; two seemingly mutually exclusive properties. It is the role of aeration in cricket pitches to negate the negative effects of the densely consolidated soil on the root system (ECB Staff, 2011) and in doing so remove the mutual exclusion of the two requirements. With the limited research into aeration outside of sandy soils it is unclear exactly how effective this is.

2.5 Soil microbial activity

The soil microbial community forms an essential link in the nutrient cycling and food webs of the soil (Bartlett *et al.*, 2008). Soil fertility and plant growth have been shown to strongly influence soil microbial size and structure (Altieri and Nichols, 2003). Hence, biological activity is often used as an indicator of overall soil quality or soil health (Warkentin, 1995; Czyż, 2004). Research relating to the microbial communities of sports surfaces has been increasing in recent years (Bartlett *et al.*, 2008; Hagley, 2002; Mueller and Kusow, 2005) but cannot be specifically related to the clay loam soils used in cricket pitches. Research on the distribution of microbial communities through the soil profile show that, in general, microbial biomass tends to decline with increased depth (Zvyagintsev, 1994; Fierer *et al.*, 2003) in line with the decrease in organic matter and root structure with depth. Soil biota differ over different geographical locations and soil types (Tiedje *et al.*, 1999). Different community phenotypes have also been demonstrated to exist at different depths within the soil profile, with the difference declining with depth down to 10 mm (Jeffery *et al.*, 2007).

The response of soil biota to compaction was reviewed in Beylich *et al.* (2010). The soil structure and the extent of compaction define the living conditions for soil biota determining the prevalence of water and air as well as influencing the oxygen and carbon dioxide concentrations. As always the response was dependent on soil type as this correspondingly affects the soil structure. Soil fauna were generally reduced by compaction due to the reduction in living space as macropores are reduced. This has an incidental effect of changing the competition and food webs which may cause further effects on other species (Beylich *et al.*, 2010). Burrowing species such as earthworms were inhibited due to increased mechanical impedance (Kretzschmar, 1991) which as a consequence reduced the habitat production created from the burrowing activity further reducing other species (Brussaard and van Faassen, 1994).

Compaction increases the habitable space for soil flora as these generally prefer smaller pore spaces. However, the increase in microporosity comes at the expense of macroporosity reducing the ability of the pore network to transport carbon dioxide and oxygen as well as limiting accessibility to organic substances that form the energy source for much of these creatures (Van Veen and Kuikman, 1990; Kretzschmar and Ladd, 1993). Overall it was concluded that the greater the bulk density the more microbial biomass was reduced despite the relative increase in habitable space (Beylich *et al.*, 2010).

Previous research found no overall effect from aeration treatments on the microbial community in cricket pitches but found aeration treatments did reduce the rate of decline in microbial biomass early in the experiment when compared to the control (Warner, 2003). It is expected that by the creation of artificial macropores, facilitating gas exchange, that microbial biomass should increase in response to aeration treatments.

2.6 Soil amelioration

Cricket pitches are primarily constructed from clay or clay loam soils. These soils exhibit shrink-swell behaviour. The shrink and swell of clay soils has been seen as one method of natural recovery for compacted soils by reducing dry bulk density and aiding the formation of stable soil aggregates (Grant and Dexter, 1990). In a cricket pitch most of the effect of rolling is concentrated in the top 50 mm (Shipton, 2008). When soils swell, the greatest amount of swelling occurs when there is no overburden and diminishes as the burden is increased (Marshall *et al.*, 1996). Like rolling, the effect of shrink-swell processes in the natural recovery of compacted soil is concentrated nearer the surface (Figure 2.5).The detailed mechanism and review of shrink and swell processes in soils is presented in Section 4.

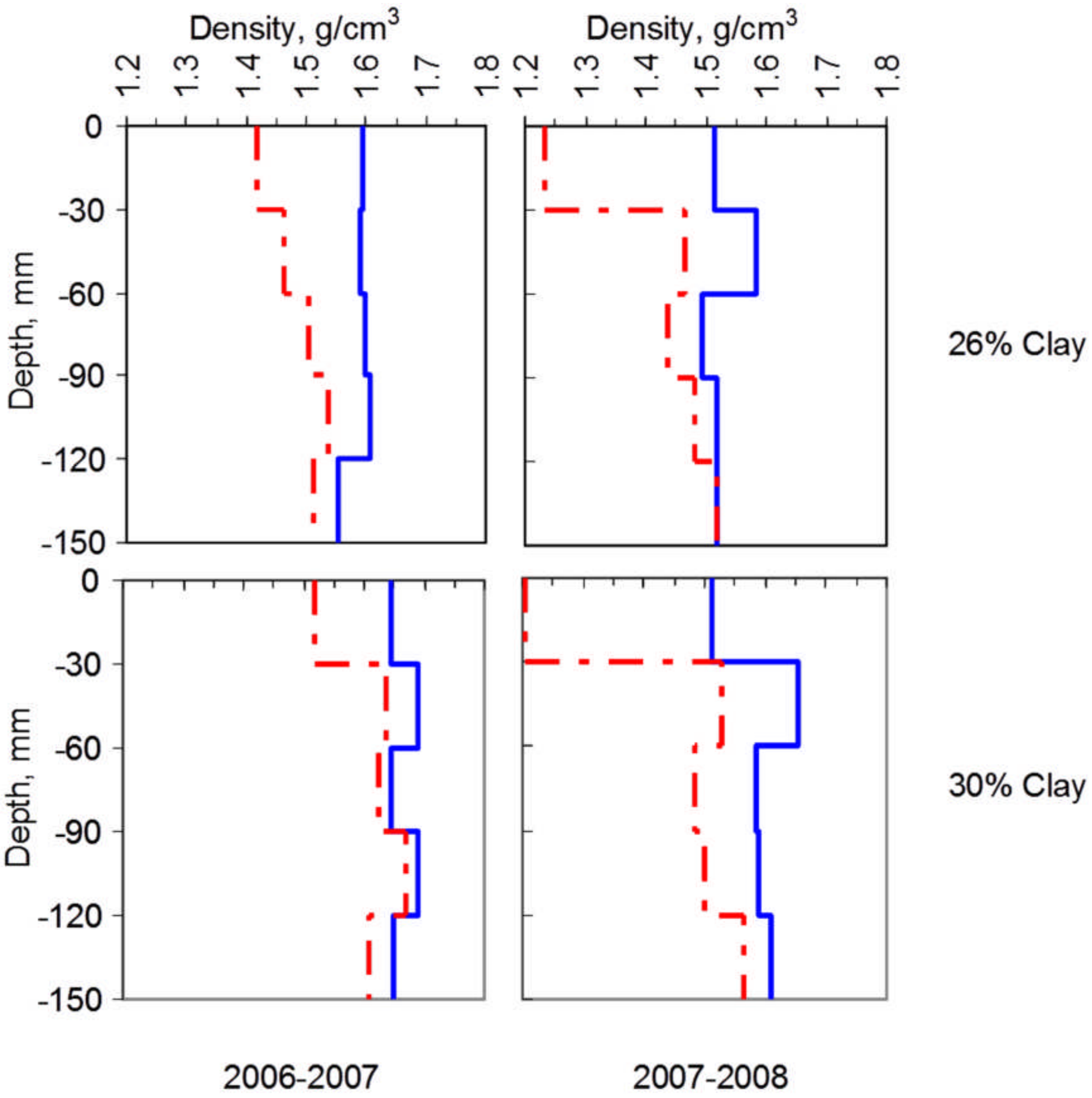


Figure 2.5 Over-winter expansion of two cricket pitch soils. The blue line represents the density of the pitch in September and the red line, the density in the following March for two winters 2006-2007 and 2007-2008 (James and Shipton, 2009).

The extent towards which the pitches can recover from the compaction effects of rolling and players by themselves is important. Firstly, and crucially, this determines whether aeration treatments are necessary or if the application of aeration should be more or less frequent as determined by the natural extent of soil recovery.

The shrink and swell nature of the clays is self-ameliorating in two ways. As the soil dries cracks form in the soil. The soil fractures along lines of weakness. These cracks increase the surface area of the soil inducing more drying and further cracking. Secondary cracks can form normal to the primary cracks, and tertiary cracks from normal to the secondary cracks (Dexter, 1991). The size and spacing of the cracks is determined by the rate of drying; fast drying produces smaller cracks with reduced spacing, slower drying produces more widely spaced, broader cracks. These cracks form potential channels for root growth, water infiltration and gas diffusion through the soil (Dexter, 1991). The inverse process, as the soil wets, closes the gaps (the rate dependent on soil type). Not all parts of the soil will receive an equal amount of water at the same time and different parts will swell at different rates. Also air trapped within the soil by the advancing water front is compressed and if not able to escape by other means can build up sufficient pressure to rupture the soil. Both these processes create microcracks in the soil (Dexter, 1988) which have been shown to increase root penetration (Dexter, 1991; Whiteley *et al.*, 1981). For this to be effective however the soil must be dry to start with and does not occur in soils wetter than -1 MPa (Dexter, 1991). Water will also relieve compaction in the soil when it freezes. Ice has a lower density than liquid water so upon freezing water within the soil matrix will expand altering the physical structure of the soil. These represent the ‘physical’ processes by which a cricket pitch could recover from the deliberate compaction of summer rolling.

Soil biota offer several ‘biological’ possibilities. The roots themselves create channels through the soil, Monocotyledons have been shown to effectively penetrate soils with up to 3 MPa resistance (Dexter, 1986). When the roots die and decompose they leave behind a biopore through which future growth of roots, water infiltration and gas diffusion can occur. As grasses will lose up to 70% of root mass over winter (Adams *et al.*, 1994) this could be a considerable effect in many cricket pitches. Other burrowing soil biota, particularly earthworms, have been shown to be particularly effective at creating biopores, increasing the pore network and aiding the formation of stable soil aggregates (Beylich *et al.*, 2010; Capowiez *et al.*, 2009).

As almost all the aeration research has been carried out in sandy soil that does not typically exhibit shrink-swell phenomena, it is unclear how the clay-based soils shrink-swell behaviour will interact with the aeration treatments, whether they will be mutually synergistic or antagonistic. An experiment to examine the amelioration of the soil under field conditions that is untreated compared to areas treated with a range of aeration techniques will examine firstly whether natural processes are sufficient on their own to relieve the compaction and whether aeration is a hindrance or a help to these natural processes.

2.6.1 Soil Aeration

Aeration was defined in Section 1 as a mechanical means of selectively tilling the soil without destroying the turf. In cricket pitches the purpose of aeration is to aid the recovery and root depth of the grass plant from the compaction effects of spring-summer rolling. Most aeration research has focused on the application of aeration treatments in sand based soils used in golf courses and modern sports field construction, no research is available for clay loams soils used in cricket pitches. Notably the UK is the only country to have the widespread use of aeration in cricket pitch maintenance (James, 2012). Aeration on golf courses has a slightly different focus than that in cricket pitches. Some areas of the golf courses are subject to considerable compaction, particularly the tee and green areas from players and from frequent mowing so compaction relief is one aim. What differentiates golf course aeration from cricket aeration is that much of the emphasis on aeration in these situations is the use of hollow tines to control thatch build-up by removing and replacing soil (Carrow, 2003; Murphy *et al.*, 1993; Carrow, 2003; McCarty *et al.*, 2007; Murphy and Rieke, 1994). Aeration in cricket pitches is generally not focused on thatch reduction but ‘relieving the dense consolidation’ (ECB Staff, 2011).

It has been established that plant roots and organisms within the soil require an adequate supply of oxygen and that compacted soils are prone to deficiency particularly under wet conditions. The supply of oxygen is considered one of the most important physical factors which limit the development of root systems and plant growth in compacted soils (Boone and Veen, 1994; Czyż, 2004; Gliński and Lipiec, 1990). Thus aeration is not principally aimed at reducing compaction but at negating the negative effects of compaction.

As seen in Section 1 as well as improving oxygen supply to roots aeration treatments are aimed at improving other soil conditions. This is by reducing soil layering, surface crusting, and helping prevent thatch build-up by increasing microbial breakdown.

Whilst aeration in other soil types is not directly applicable to cricket pitches the trends observed act as a useful comparison. The effect of several aeration techniques on soil bulk density have been examined.

Murphy *et al.* (1993) found that solid tine cultivation did not affect soil bulk density in a loamy sand over the course of a year. Murphy and Rieke (1994) found that water injection decreased soil bulk density in a loamy sand over a year compared to solid tines but not compared to the control. Several studies measured penetration resistance as an indicator of aeration effectiveness in sandy soils; reporting a short-lived effect of between 1-10 weeks of reduced penetration resistance from solid tine aeration (Guertal *et al.*, 2003; Murphy *et al.*, 1993; Morhard and Kleisinger, 2004; Prämaßing *et al.*, 2009). Prämaßing *et al.* (2009) found in a loamy sand that the effects of Solid Tine cultivation and Water Injection sometimes decreased penetration resistance but could also increase it. This was attributed to changing soil conditions on treatment application. Morhard and Kleisinger (2004) found that finer soils (a sandy loam compared to a sand) showed shorter-lived effects from aeration than coarser soils but overall aeration gave positive effects, reducing penetration resistance and increasing oxygen concentrations.

Solid tining has been shown to cause compaction below the depth of tine penetration reducing soil hydraulic conductivity (Brauen *et al.*, 1998). Solid tine aeration produces compaction around the edges of the tine hole, in sandy soils this will crumble away and does not present a problem (Murphy and Reike, 1990), however on the clay loam soils present in cricket pitches this may not be the case. The increased cohesion of the clay dominated soil prevents the crumbling and collapse observed in the sand. Shrink-swell and freeze-thaw processes will remediate the compaction in the clay-loam eventually but this relies on repeated wetting and drying cycles or freezing and thawing weather giving an uncertain timeline for the process.

The deep drill is considered a good technique for the aeration of cricket pitches due to its perceived lack of compaction of the tine holes when it penetrates the ground and its ability to penetrate the very hard clay soils present to depths exceeding 20 cm (Nektarios *et al.*, 2004). Drill aerators do not relieve compaction in between drill holes (Brown, 2005) but have been shown to increase deep infiltration of water into the profile in sand based soils (Nektarios *et al.*, 2004).

In summary, the effects of aeration observed tend to be short-lived (1-10 weeks) and variable in their effect, sometimes producing measurable decrease in compaction, and sometimes not. The research has focused almost exclusively on soils containing little or no clay, so the interaction of shrink-swell and the addition of the fine-textured clay component to soil structure has not been considered in its effects on aeration effectiveness.

2.6.2 Deformation of soil

The timing of aeration treatments is of key importance in how the treatments effect the soil structure. In the clay loam soils of cricket pitches this is almost entirely dependent on water content.

Soil has three basic states, solid, liquid and plastic. The state of the soil is dependent on water content (Figure 2.6). Soil in a plastic state is a non-Newtonian fluid and will flow when a stress is applied greater than a critical level, the yield stress. Solid soil will fracture rather than flow once the yield stress has been reached. Liquid soil behaves as a Newtonian fluid and will flow with zero yield stress. Among other factors the yield stress of the soil is dependent on water content, generally the lower the water content the greater the yield stress (Jury and Horton, 2004). The solid state is divided into two categories ’friable’ and ‘hard’ separated by the relative ease with which the soil can be fractured, friable being the easier of the two.

The liquid limit defines the water content at which the soil passes from a plastic to a liquid state, similarly, the plastic limit delineates when the soil passes from a solid to a plastic state. The difference between the plastic limit and the liquid limit is the plasticity index (Marshall *et al.*, 1996).

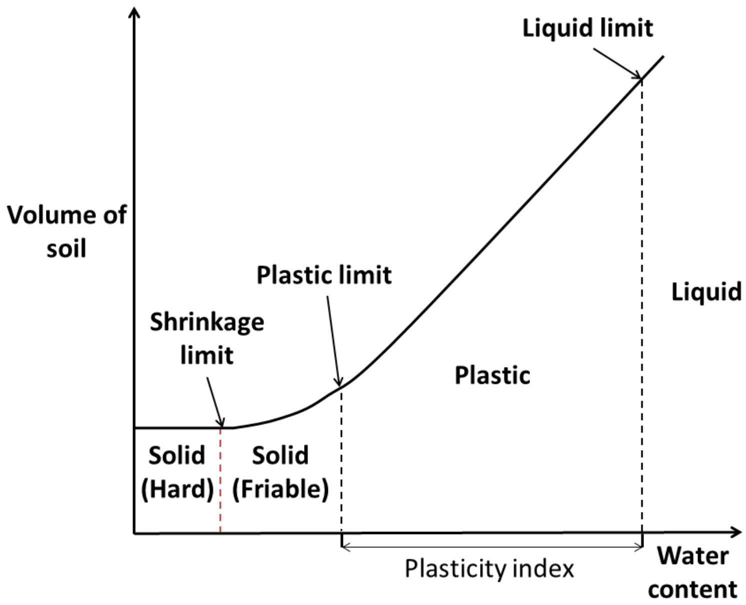


Figure 2.6 Hypothetical volume of soil plotted against water content delineating the three states of soil and the boundary limits for each phase (Marshall *et al.*, 1996).

The limits help define the properties of the soil for engineering use as well as acting as a guide for when particular tasks will be most effective, e.g. agricultural tillage operations. If tillage is applied when the soil water content is greater than the plastic limit the soil will smear and deform. If the water content is below the plastic limit the soil will fracture which is the aim. If the soil is too dry and below the shrinkage limit considerably more energy is required to cause the soil to fracture increasing fuel consumption and stresses on machinery. Similarly aeration has an optimum water content for application yet this depends on the objectives to be achieved. Solid tine, slit/knife and linear aeration will be most effective at increasing porosity and surface area if conducted below the plastic limit when the soil will fracture rather than deform. The effectiveness of the deep drill should not change as this will be unlikely to fracture the soil but could be improved if done below the plastic limit to avoid smearing the soil. However, creating lots of cracks in a cricket pitch also creates lots of lines of weakness from which cracks are more likely to form as the soil shrinks in the summer (Dexter, 1991). In addition, the high density clay loam soils used to construct cricket pitches will have a relatively high soil strength and thus in the solid state may be resistant to penetration thus aeration at this time is mechanically unfeasible due to excessive wear, insufficient power or normal load (reaction force) in the machinery. Even if penetration is achieved the high soil strength will limit the working depth of the machine.

Typically aeration is carried out in mid-autumn when the soil water content has increased and the soil strength reduced so that the soil is generally in a plastic state (ECB Staff, 2011). Thrusting the solid tine into the soil is similar to the penetration of the soil using a cone penetrometer. Farrell and Greacen (1966) found the forces acting against the cone penetrometer were a combination of the soil shear strength, compression of the soil ahead of the tine and metal-soil friction. Of these, soil shear strength and compression of the soil are more easily achieved by increasing the water content (up to a point). Whilst it is easier to aerate soil in a plastic state rather than a solid state and greater depths can be achieved, the soil will deform and compress rather than fracture so the overall effectiveness will be reduced. In cricket a balance must be struck between effective aeration, working depth, wear and stress on the machinery whilst ensuring the profile is not weakened such that large cracks form in the summer time. Cricket pitches in the UK are constructed from such a wide variety of soils in a range of microclimates (Shipton, 2008) with variable organic matter contents, and profiles (e.g. depth of cricket loam on natural soil, layering) that defining an optimum water content for aeration is practically impossible as it will be unique to each pitch and more likely defined by the machinery available in terms of its power, reaction force and durability.

2.7 Diffusion of innovation

The intended output of the project for the sponsors is a set of guidelines for best practice in aeration. For these guidelines to be effective in the improving standard of pitches across the country they must be embraced by groundsmen. Each groundsman acts autonomously and is individually responsible for the pitches under their care. As such the guidelines cannot be forced upon them and must be voluntarily incorporated into their maintenance decisions. A large volume of work has been carried out that describes the flow of new inventions through a population and the basic theory is outlined below.

The diffusion of innovations is a theory that describes how, why and how fast an innovation is spread through a social system (Rogers, 2003). In this case the innovation is the guidelines on aeration. The innovation is passed through certain communications channels over time among the members of a ‘social system’. The ‘social system’ is defined as a set of interrelated units attempting to solve a common problem, or more simply, those who benefit from the innovation, and could be any size from individual people to corporations or governments but here represents the cricket groundsman community. There are four main elements that influence the rate and extent of uptake: the innovation itself, the communication channels of information on the innovation, the time taken for the decision to use the new innovation and the social system in which the innovation is attempting to spread (Rogers, 2003). Each factor will be considered in turn.

The innovation itself will influence the rate at which it is employed through five general properties: the relative improvement that is offered over the previous generation, the compatibility with existing systems (i.e. how easy is it to assimilate into current practise), the complexity (how simple is the innovation to use), the observable effectiveness of the new innovation and the trialability (how easily can the innovation be tested for the above factors). The best innovation in terms of the rate of uptake will offer a clear observable improvement over the previous generation, that is simple to use, integrates well with the existing systems and can be easily demonstrated to do so with the minimum of effort, disruption and cost. An example of such an innovation would be GPS navigation compared to paper maps. The worst-case scenario is an innovation that is (or thought of as) offering little improvement on resident alternatives, that is more complex to use and difficult to integrate into current practise and has a non-visible or intangible effect that cannot be easily quantified. An example of such an innovation could be DAB radio compared to FM, or the now scrapped government ID card scheme compared to passports and driving licence photocards. Therefore when designing the guidelines they should be simple to understand and thus easy to implement. It may be difficult to provide a tangible and observable difference as most of the aeration effects occur below the surface and may take time to manifest in pitch performance so it is imperative that a clear and logical reasoning is provided in the guidelines for implementation so that groundsman have the confidence to risk the new innovation. It is the potential lack of a clear observable difference that may be the most difficult aspect in the widespread uptake of the guidelines.

The communication channels refer to the methods by which knowledge of, and about, the innovation is spread from one individual to another. The two most influential methods are mass media and interpersonal communications (van Eck *et al.*, 2011). Mass media is most effective at creating an awareness of the innovation. Interpersonal communications are more effective at forming and influencing attitudes towards the innovation particularly regarding the decision as to whether to accept or reject it (Gelb and Johnson, 1995). In this decision, generally, evaluation of the innovation by near-peers is more influential in the decision process than scientific research by experts (Rogers, 2003). In terms of the guidelines almost all communications will be from near-peers as mass-media is unlikely to be advertising aeration guidelines due to the very limited market. Mass-media in this case is limited to IOG and ECB publications and presentations which requires a commitment and dedication from these organisations to fully support and embrace the new guidelines if they are to succeed.

The time element consists of two main components, the time required to proceed through the decision process and the ‘innovativeness’ of the individual. The decision process can be subdivided into five components and describes the time from initially becoming aware of the innovation through to final acceptance or rejection of it. Rogers (2003) defined the five steps as:

1. Knowledge – the individual is exposed to the innovation but lacks information about it and at this stage is not enthused to discover more.
2. Persuasion – the individual is interested in the innovation and is actively seeking more information.
3. Decision – the individual weights the advantages and disadvantages of adopting the innovation and decides whether to accept or reject it.
4. Implementation – the innovation is applied to varying degrees (from trial to full implementation) where the in-situ effectiveness of the innovation is determined.
5. Confirmation – The decision of acceptance or rejection is re-evaluated in light of the knowledge gained from implementation.

The time taken to proceed through all five steps is dependent on the individual and the innovation itself, how easy it is to trial, the effectiveness of communication channels, and so on. The ‘innovativeness’ of the individual is linked in with this and describes the whether the individual is slower or faster in adopting new innovations. The five categories, their order, and size are shown in Figure 2.7.

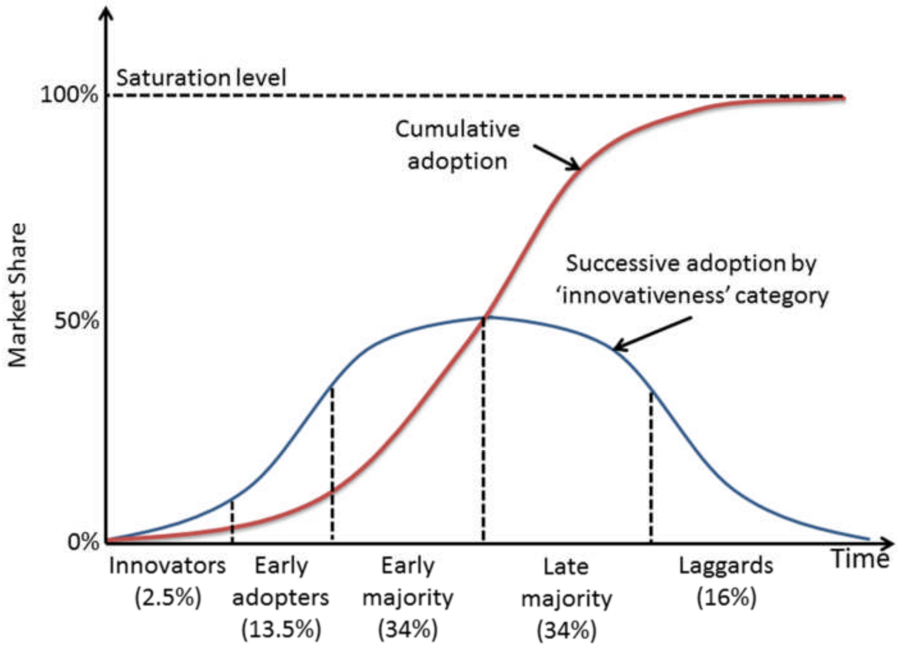


Figure 2.7 Uptake of an innovation through a social system by 'innovativeness' categories, showing the relative size of each group. Adapted from (Meade and Islam, 2006).

Innovators are the first to adopt a new innovation and tend to be small in number, often being described as 'obsessed' with new ideas. This keen interest tends to lead innovators out of their localised peer group and into 'innovator' peer groups. Innovators tend not to be widely respected and so are generally not opinion leaders however they act to bring new innovations and ideas into the localised peer group where it is then exposed to early adopters. Innovators tends to have high levels of resources able to cope with failed innovations and a high level of understanding and knowledge. Early adopters form a larger proportion of the system and tend to be the most influential. Potential adopters look to the early adopters as role models who tend to be not too far ahead of most individuals in innovativeness and embody the successful use of new innovations through selective and judicious use of new ideas and technology. Early adopters help to spread the new innovation acting as local ambassadors reducing the uncertainty in the innovation. Opinion leaders are generally early adopters because of this. Early majority adopt an innovation just before the average member. The most fitting description of an early majority individual is a deliberate willingness to adopt new innovations but will seldom lead the adoption of one. Adoption by the early majority provides interconnectivity between the early adopters and the late majority providing the critical pressure that encourages the late majority to adopt the innovation. The late majority are sceptical and cautious, often due to limited resources and require most of the uncertainty to be removed before considering a new innovation. The final category is laggards. Laggards tend to be near isolates in the social system and decisions tend to be based on what has been done previously, their point of reference being grounded in the past. Laggards are suspicious and very cautious, they must be certain that a new innovation will not fail before adopting it. The ‘innovativeness’ of a population is an intrinsic property and so the cricket groundsman community can be expected to follow similar behavioural patterns. The population in this case is relatively small so the number of innovators will be proportionally smaller therefore they must receive careful support to encourage the spread of the guidelines in the early stages.

The final element is the social system. This defines the boundary within which the innovation diffuses and its structure affects the effectiveness of various communication channels as well as determining potential barriers to change. Norms describe the established behaviour patterns of individuals in the system. An innovation that is incompatible with the norms of the system will not be adopted as eagerly and may result in complete rejection and so help define the resistance to change in a system. Already it has been stated that inter-personal communication is a key communication channel and important in the innovation-decision process. It has been noted that some individuals are more influential than others the most influential of whom are termed ‘opinion leaders. Opinion leaders tend to be highly respected individuals who generally have greater exposure to the mass media, are more innovative (innovator or early adopter categories) and more exposed to new innovations (and those advocating the innovation). Opinion leaders serve as role models for many members, stimulate discussion and generally increase the uptake of an innovation (van Eck *et al.*, 2011). Once uptake has reached a certain proportion it becomes self-sustaining a point called the critical mass. Critical mass occurs once a sufficient number of people have adopted the innovation in the social system such that the rate of adoption becomes self-supporting and creates further growth (Rogers, 2003; Mahler and Rogers, 1999).

There are several ways in which the diffusion process can be accelerated or encouraged:

1. Adoption by a highly respected individual leader (the opinion leader of opinion leaders) or a group of opinion leaders
2. Creating an instinctive desire for the product e.g. by implying that the adoption of the innovation is inevitable or very desirable
3. Injection of the innovation into an eager group rather like sending the product out to the innovators rather than waiting for them to adopt it essentially kick-starting the process.
4. Positive reaction and benefits for early adopters, such as discounted prices or other financial benefits

Of these only strategies one, two and three are conceivably possible in this case. As the guidelines are free, option four is irrelevant unless someone is willing to pay groundsmen to adopt them which is highly unlikely. Option two would also be difficult due to the autonomous and independent nature of the individuals involved. The best option would seem to be a mix of options one and three with the injection of the guidelines into a group of opinion leaders or those that will be formed into opinion leaders to act as ambassadors and role models for change.

In order to achieve a successful deployment of the guidelines and uptake into the groundsman community a carefully planned strategy must be created. An understanding of the structure of the community and the communications channels that exist between groups defining who the opinion leaders are and how widespread their influence is, i.e. does every groundsman come into contact with all the others or do they exist in local groups with limited intergroup communication, so will there be a few national opinion leaders or an opinion leader for each group.

2.8 Summary of literature review

The grass plant is an essential component of a cricket pitch adding to the strength of the soil to reduce crack formation and surface wear but most importantly as a conduit for moisture removal from the soil, particularly at depth, to achieve the very high bulk densities required. To achieve efficient water removal the root system of the plant must be widespread and penetrate sufficiently deep into the profile a requirement that is in direct contradiction to the growing environment of a compacted soil.

The compaction of the soil creates not only mechanical impedance to root penetration but also reduces the transport capability of the soil for gas diffusion and water. Compaction has been shown to increase the likelihood of developing a hypoxic or anoxic environment in the soil which will retard root growth.

The purpose of aeration in cricket pitches is to negate or reduce the effects of compaction in order to create a more favourable growing environment for the grass roots. The amount of research into aeration is small in volume and focused in sandy soils, there has been no direct research before on aeration in cricket pitches or in clay dominated soils in general. Nor has aeration been considered for its effects on the microbial communities in the soil which are also affected by soil compaction. Thatch develops when the rate of organic matter production exceeds the rate of decay (or removal). Whilst mechanical techniques exist that can remove much of the organic matter down to a depth of 20 mm the soil microbial community is responsible for the decay of the remaining material. Considering that ideally root depth should exceed 100 mm and that the plant sheds up to 70% of its root system each year a considerable amount of organic material will remain that cannot be removed mechanically. Thus an effective soil microbial community is essential. This leads to two research questions:

1. *What effect does aeration have on the soil microbial community?*
2. *What effect does aeration have on the development of thatch?*

The ECB guidelines detail when and how to aerate but the evidence upon which these are based are anecdotal and primarily based on the subjective experience of the end-users. The lack of dedicated scientific research leaves fundamental questions regarding the effects of aeration in clay loams unanswered. Fundamentally there is no real understanding of the true effects of aeration in cricket pitches and how these relate to benefits in root penetration and ultimately the playability of pitches. Therefore, before the optimisation in the application regimes of aeration techniques can be considered the research must focus on understanding the underlying actions of the various aeration treatments on the soil physical structure and soil atmosphere.

It was seen from the work carried out in sandy soils that the penetration resistance and bulk density of the soils was sometimes reduced by aeration but not consistently and when observed was of short duration. If the soil was decompacted to an extent by aeration this would improve the growing conditions for the grass plant and could be one mode of action by which aeration may aid deeper root penetration. The shrink-swell behaviour of cricket pitch soils will naturally reduce the bulk density of the soil as the water content increases and it is important to discover whether this is more effective than aeration or whether aeration can aid this process or hinder it. Several research questions are needed to address this:

3. *What effect does aeration have on soil physical properties?*
4. *To what extent does the natural shrink-swell of soils reduce soil compaction and how can this be used to the advantage of groundsmen?*
5. *How long do the effects of aeration last in cricket pitches?*

Aeration creates large artificial macropores in the soil. The aim of these macropores is to increase soil infiltration, hydraulic conductivity and gas exchange thus negating many of the negative effects of soil compaction outlined above. It was seen that soil in a plastic state will deform and smear rather than fracture. Aeration is principally carried out when the soil is in a plastic state in cricket pitches due to the hard nature of the soil when it is in a solid state and as such particularly when using solid tines this creates compaction around the tine hole as well as smearing so that the soil is compressed and deformed by the entry of the tine. The increased compaction around the newly formed artificial macropore may in effect remove much of its effectiveness to act as a conduit for increased gas exchange and water transport. Three main research questions can be derived from this:

6. *Does the compacted soil of a cricket pitch create hypoxic and anoxic environments that could restrict root growth?*
7. *How much does aeration increase the gas exchange capability of the soil?*
8. *To what extent does aeration improve the soil atmosphere for root growth?*

Using the information to date, the identified knowledge gaps and the research questions the following aims and objectives for the research project were established.

2.9 Aim and Objectives

Aim: To gain a fundamental understanding of the effect of aeration processes on the soil physical properties and biological health of clay-soil sports surfaces.

Objectives:

1. Conduct a thorough and extensive review of past and current research into soil aeration.
2. Investigate and evaluate the effect of aeration on soil gas exchange through the development of a technique to reliably measure changes in soil atmosphere.
3. Examine the effect of aeration on infiltration rates, water retention and natural wetting/drying cycles of soils.
4. Investigate and evaluate the effect of aeration on soil mechanical parameters, particularly soil strength and surface elastic-plastic behaviour.

5. Survey and analyse the effect of aeration on soil microbial activity and the biological health of the soil and plant growth.
6. Evaluate and assess the effectiveness of different aeration techniques and equipment in field trials using the knowledge and methods gained from 2-6.
7. Make recommendations to practitioners for improved effectiveness and efficiency in the treatment choice and application of aeration in cricket pitches.

3 Current aeration practices

3.1 Introduction

The variation in aeration practices over the year on Cricket pitches in England and Wales is unknown. Management decisions on aeration are without clear guidelines and therefore informed from personal experience and anecdotal evidence. The range of techniques available further complicate the matter with several different modes of action (Section 1) as well as variations in the frequency of application.

The range of aeration techniques is believed to stem from the variety of ideas as to the purpose of aeration in cricket pitches. The question is whether it is a routine technique to be applied regularly with consistent benefits or a technique to be applied to solve certain problems such as root breaks and layering in the profile.

This survey was designed to assess general aeration practices and the current thinking behind its application in order to illuminate where the greatest discrepancies are between beliefs surrounding aeration and the evidence-based conclusions of this report so that any guidelines can be best tailored to address this.

3.2 Survey design and distribution

A survey questionnaire was designed to allow respondents to give basic construction and usage information on their facilities as well as the aeration equipment and application regime they use. The final section focuses on attitudes to aeration and its uses as to what the groundsman expects from the aeration treatment in terms of benefits to the pitch.

The majority of questions were designed to be multiple-choice incorporating as many expected answers as possible. Shipton (2008) found that open-ended questions whilst providing the most information are unsuitable for numerical analysis.

A draft copy of the survey was assessed by a Cricket Pitch maintenance course instructor, a retired First-Class groundsman and two school groundsmen for suitability and ease of completion before general distribution. Copies were distributed at all regional IOG meetings and provided to ECB Pitch Advisors for distribution to as many Cricket groundsmen as possible. First class groundsmen received questionnaire copies individually at the ECB annual groundsmen's conference. The questionnaire was also available to fill in online through Bristol Online Surveys, with links from the project website as part of the Centre for Sports Surface Technology website.

The survey was conducted between September 2009 and September 2011. Results were analysed using Statistica 10 (Statsoft, Tulsa, USA) using parametric and non-parametric tests.

3.3 Results

3.3.1 Survey response and population coverage

105 useable questionnaires were returned for analysis though not all questions were answered in every response. There are 3951 affiliated clubs and 7064 cricket facilities in England and Wales (James, 2012b) this corresponds to 2.7% of affiliated clubs and 1.5% of facilities covered in the survey. The distribution of facility type in the sample population is shown in Figure 3.1. There were no responses from any municipal facility possibly indicating a gap in survey distribution coverage. The response from First class facilities was 61% from a total of 18 facilities. Only 10 schools were captured in the survey possibly under representing this group.

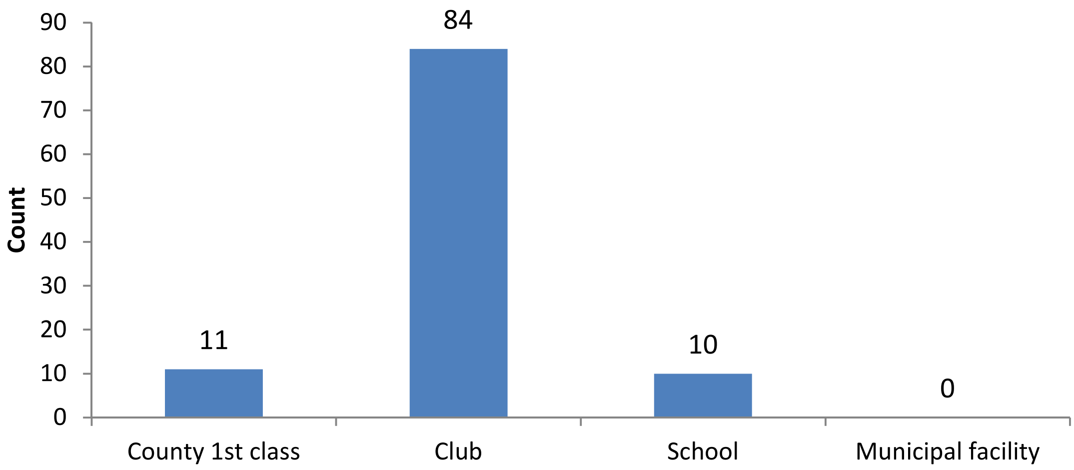


Figure 3.1 Survey responses categorised by facility.

3.3.2 Pitch usage

The number of pitches (defined by the number of useable strips on a square), number of games and number of games per pitch were analysed for differences between facility types. The number of pitches and the number of games per pitch were significantly different between facility types. The analysis used was the Kruskall-Wallis which is a non-parametric equivalent of ANOVA. Unlike ANOVA however the Kruskall-Wallis test cannot identify differences between pairs, only whether there is or is not a within-group significant difference, for example, the test shows there is a significant difference in the number of pitches by facility, unlike ANOVA it cannot show if the difference exists between club and first class or club and school. Examination of the data presented in Figure 3.2 shows that the number of pitches in school facilities tends to be greater than at club and first class but this may be due to the pitches in schools being spread over a number of squares rather than in a single square in most clubs due to the nature of the facility. The number of games per pitch tends to be considerably lower in first class than at club or school level. This is in line with the findings of Shipton (2008).

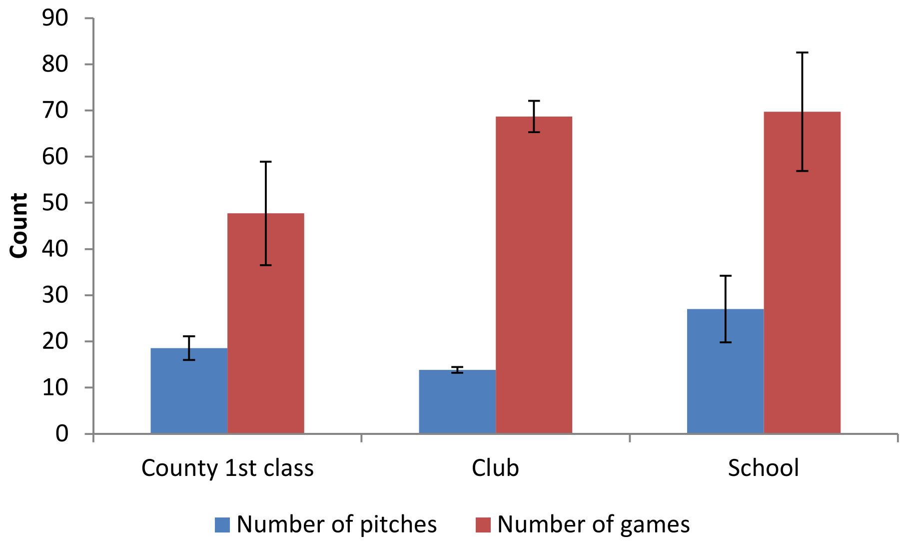


Figure 3.2 Mean number of pitches and number of games per season for each facility type.

3.3.3 Trends in general maintenance

Scarification is a common autumn treatment and all respondents used scarification in various forms as part of their autumn renovations. Three categories are examined here. Light scarification is achieved by vertical blades that just scratch the surface of the soil to remove organic matter that has built up on the surface. Deep scarification involves the penetration of the soil by the blades to remove organic matter in the top 20 mm of soil. Deep scarification is Linear Aeration, the survey was designed to accommodate the fact that Linear Aeration is often not seen as an aeration treatment but just a more thorough scarification treatment. Fraise mowing physically removes the top layers of soil to a set depth. The distribution of treatments between facility types is quite different, with a trend towards deep scarification in place of light scarification in First Class facilities as well as a small minority incorporating Fraise mowing as part of the general cycle (Figure 3.3). It was noted from comments that the Fraise mowing treatments were conducted on a section per year of the square on a rolling basis so that the whole square was covered over a five year period rather than treating the entire square. So long as the depth of soil removed does not exceed 50 mm then it is usually possible to play on the pitches the following year. The decision to apply the treatment in stages is believed to be primarily because of the high financial cost of the treatment and reducing the risk of having the entire square unsuitable for play if everything does not go according to plan.

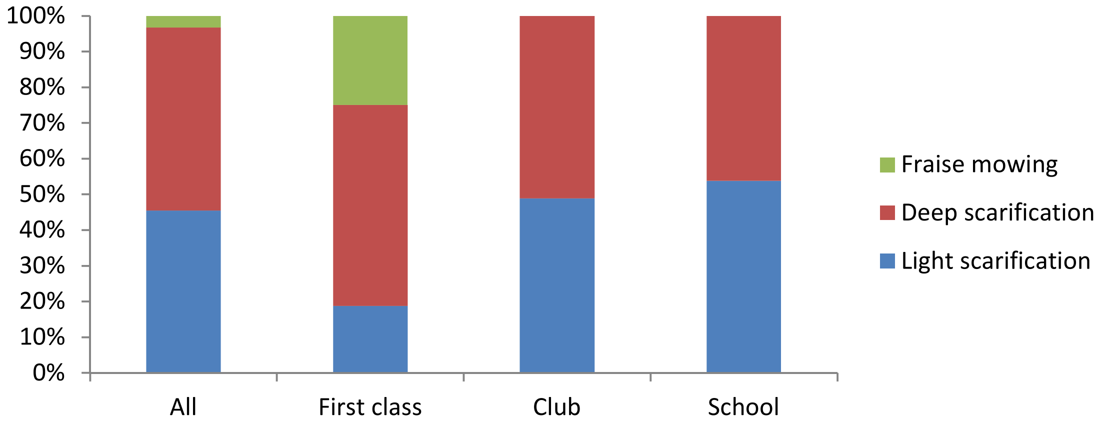


Figure 3.3 Prevalence of scarification types overall and in different facility types.

Fraise mowing is also used in response to problems in the upper soil profile related to organic matter and layering that cannot be solved through other means. It is possible that the usage is limited by cost as when asked if Fraise mowing had ever been used only 8% of clubs have compared to 45% of First class grounds.

The spiked roller, generally consisting of a small diameter drum fitted with short (approximately 50 mm) tines, is utilised by an equal proportion of groundsmen across all facility types (64 ± 2 %). This shallow tine spiker is also classed as a form of aeration used to open the surface and prepare a good seed bed, hence it is often utilised in post-match renovations (Figure 3.4).

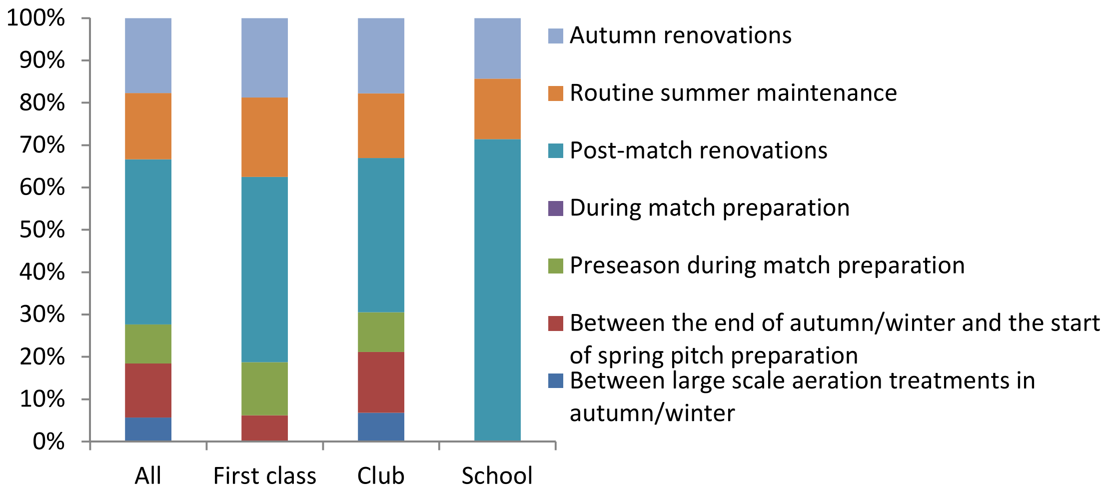


Figure 3.4 Use of spiked roller in various general maintenance tasks throughout the year on a cricket pitch.

Usage between First Class and Club is quite similar though the First Class groundsmen do not report usage in winter possibly to avoid unnecessary traffic on the square during the wet winter months when the damage done can potentially outweigh the benefits (Section 7.3). Noticeably the school group does not use the spiked roller outside of post-match renovation, routine summer maintenance and autumn renovations. This indicates that the school groundsmen consider the application of the spiked roller as unnecessary if the pitch has been treated with larger scale aeration treatments for over-winter recovery.

3.3.4 Aeration treatment choice and usage

Generally aeration is seen as an annual treatment, particularly at club and school facilities where 90% of them report annual operations. This trend is echoed at First class level but slightly reduced to 82% with the remainder treating biennially (Figure 3.5). Shipton (2008) reported a number of First class facilities that claimed never to aerate which is not repeated here. Potentially in such a small population the groundsmen responsible responded to one survey and not the other. Alternatively the practise has fallen out of favour and groundsmen are aerating again. The choice not to aerate at all appears to have a small following at club level but it is unknown whether this is because groundsmen feel they have no need to aerate or because they do not have access to equipment.

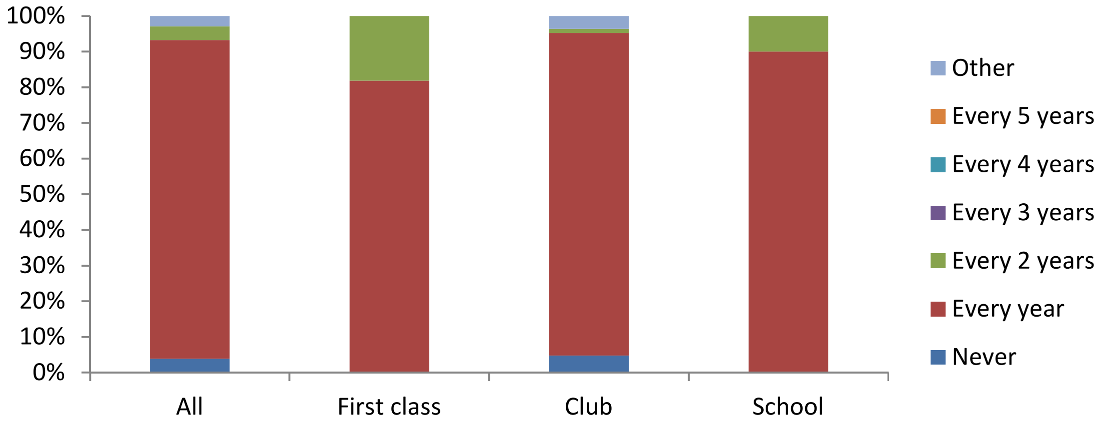


Figure 3.5 Proportional representation of aeration treatment frequency by facility type and over the entire sample.

In all facilities the dominant treatment is a vertically operated tine (VOT) (Figure 3.6), of which 93% use solid tines. The minority use of hollow tines is limited to clubs only.

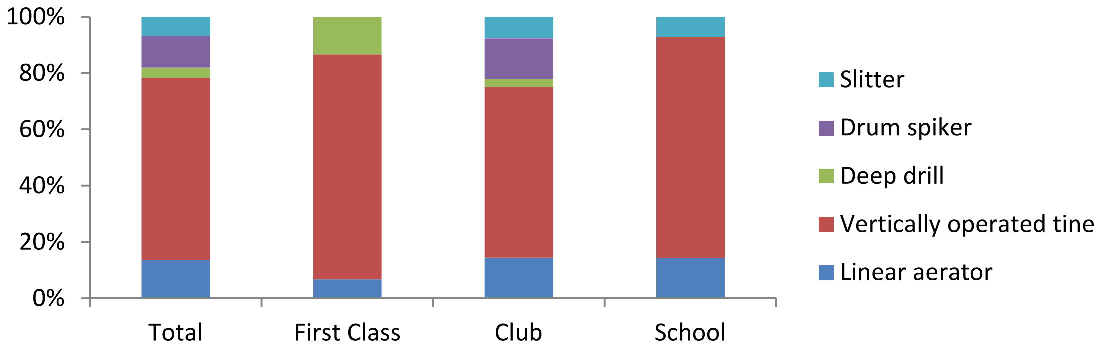


Figure 3.6 Proportional representation of aeration treatment types used by facility type and over the entire sample that choose to use aeration.

The noticeable lack of the use of slitter type aeration from First Class facilities compared to Club and School is reflected in the generally held fear that slits will create lines of weakened soil bonding that will in summer time reopen as large cracks. The choice to use drum spiker treatments generally stems from there being only two options of either the drum spiker or nothing with 50% of users reporting them as the only machines available and the vast majority of the machines when used are owned by the club (Figure 3.7).

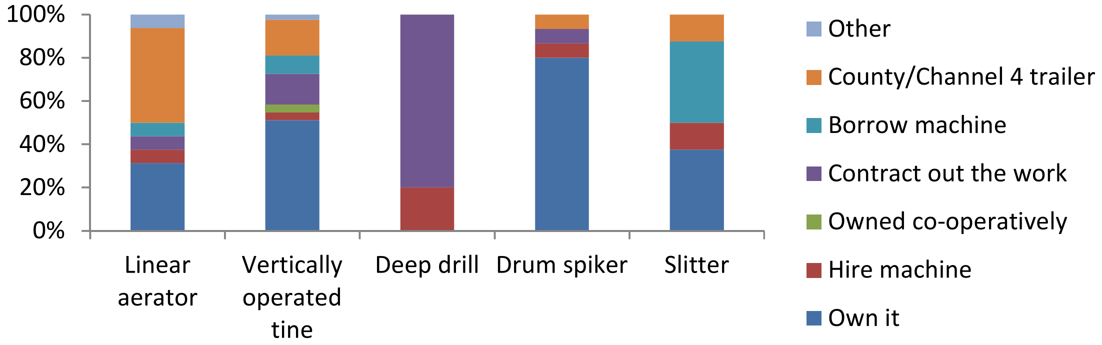


Figure 3.7 Proportional representation of aeration equipment sources across all facility types.

Different aeration modes of action are applied with varying frequency. The VOT and drum spiker are applied with greater frequency than the remaining treatments. The limited application of the deep drill has repercussions in its effectiveness at thatch reduction by physically removing soil as the relative turnover of soil on a yearly basis will be very small.

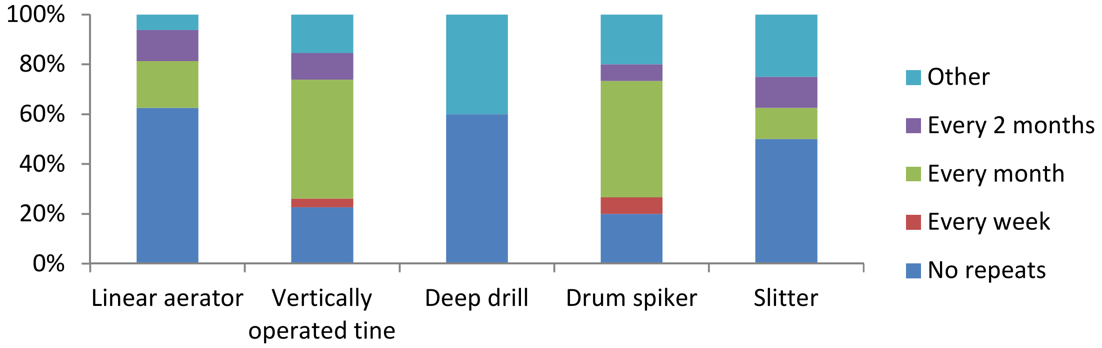


Figure 3.8 Frequency of application of aeration treatments across all facility types.

The linear aerator is generally only applied once but this could be due to the view of it as a general maintenance addition or variation to scarification as generally linear aeration is applied as an end of season treatment whereas the other aeration treatments are applied later depending on soil conditions separate from general autumn maintenance of scarification, seeding and topdressing (Figure 3.9). The deeper penetrating techniques of deep drill, VOT, drum spiker and slitter require the soil to be wetter with subsequently reduced soil strength in order to achieve effective penetration. This leads to a delicate balance between machine wear and treatment effectiveness as the harder the soil the more the tines will wear as well as general strain on machinery whereas a very wet soil will be compacted from the traffic and will smear and deform.

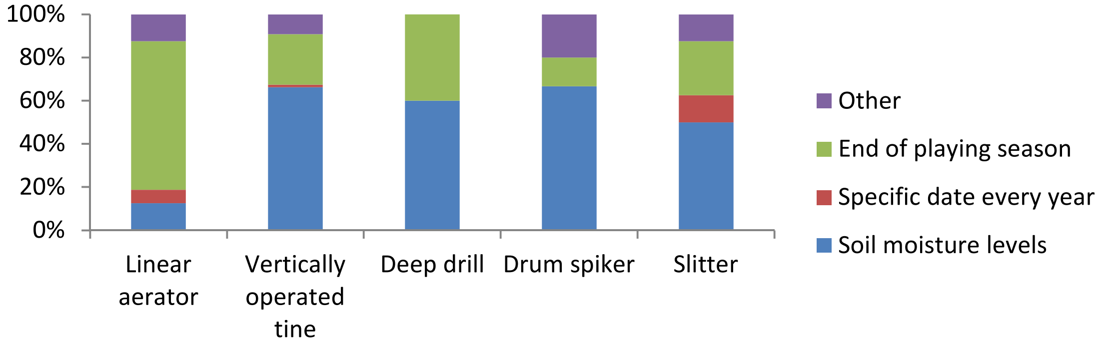


Figure 3.9 Factors determining the start of aeration for each treatment across all facility types.

The cessation of aeration treatments is generally January but weather has a strong influence so this question does not really cover the entire decision process as if the pitch is frozen or covered in snow then there will be no aeration regardless of date. The choice of a date for the cessation of aeration in the majority of cases rather than on water content may indicate a lack of understanding of the effectiveness of aeration under differing soil conditions.

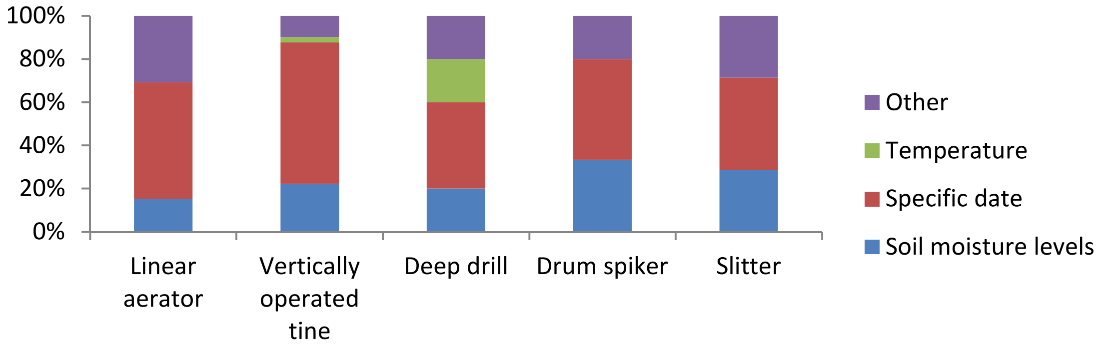


Figure 3.10 Factors determining the end of aeration treatments across all facility types.

The duration for which each treatment type has been used regularly on the pitch is shown in Figure 3.11 and reflects the general trends in the industry regarding aeration, with the relatively new treatments of the deep drill and linear aerator having been used only for a few years and the gradual adoption of the vertically operated tine (VOT). Interestingly the drum spiker shows an equal short term and long term split with half using it for over 8 years and the remainder for 3 years or less, perhaps representing two populations those that own the equipment and have used it for years and those adopting recently. Drum spikers are substantially cheaper than VOT systems. (roughly 50% cheaper for pedestrian units and up to 83% cheaper for tractor units) which is a strong incentive for choosing this treatment particularly for a poorly resourced club despite the strong recommendations not to use drum spikers. This could indicate a trend that any aeration is thought to be better than no aeration even if the particular aeration treatment is recommended against.

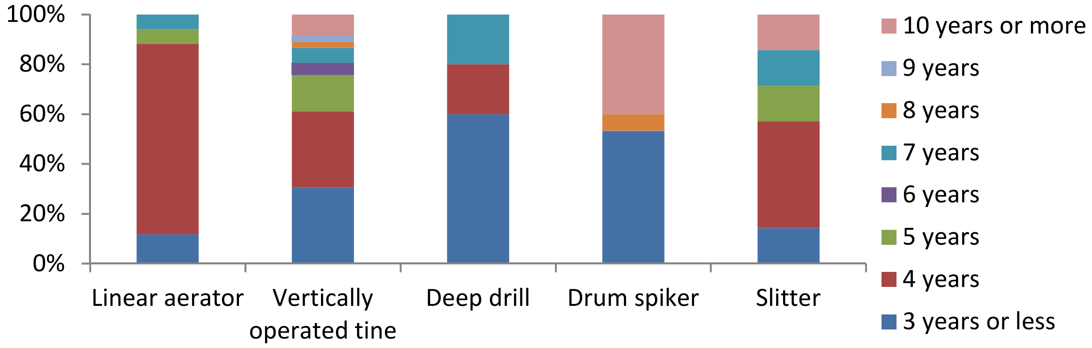


Figure 3.11 Proportional representation of the duration of successive aeration treatment applications for each treatment type.

The long term use of the same machine operating to the same depth has been highlighted as a potential source of compacted hard pans in the soil profile (Rieke and Murphy, 1989) particularly when using solid tines.

When asked how the cost of the machines influenced their decision to aerate, the response was generally of little influence (Table 3.1). One-way ANOVA revealed no difference between machines as to cost influence on decisions.

Table 3.1 Influence of the expense of aeration treatment on machine choice.

How do the influences below affect choice of aeration treatment on a scale of 1-10 (1 no influence, 10 strongly influenced)	Score	
	Mean	St. Error
Overall cost	2.9	0.3
Cost of obtaining and or maintenance	2.3	0.2
Time required to apply the treatment	3.2	0.3

The relatively low importance of cost appears to be because the majority of facilities either own the equipment or gain access to it through economical means such as borrowing it or from the County/Channel 4 trailer (Figure 3.7). A notable exception is the deep drill, which must be hired or contracted, but as this is primarily used in First Class grounds that generally have greater resources the reported cost influence will be proportionally less.

3.3.5 Root breaks and layering

54% of respondents reported that they knew of a root break or non-binding layers in the soil profile. 12% did not know, leaving only 34% who were confident that there were none. The prevalence of root breaks in the First Class pitches was higher than the other facility types, with 73% reporting root breaks or layering (Figure 3.12).

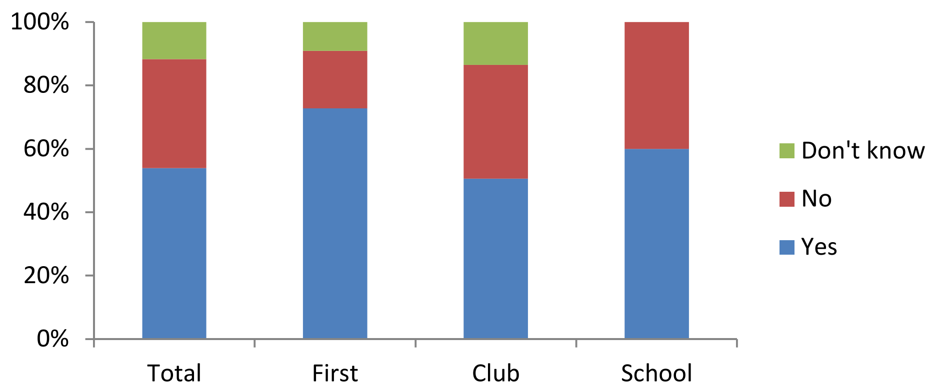


Figure 3.12 Prevalence of breaks in the soil profile for each facility type and overall average.

This does not necessarily mean that there is a greater prevalence in First class pitches compared to Club or School facilities, this could simply be due to the generally greater resources and training available in the First Class facilities so that they are more aware of them. The ECB has issued all First class facilities with a split corer (BMS Products, Luton, UK) in order for them to take cores of their pitches to examine the soil profile. Club and School facilities may not have access to such equipment and consequently may be unaware of root breaks in the profile.

The presence of root breaks and layering even at the top levels of the game, indicate this is a serious problem facing the industry particularly as the only way to be totally sure of fixing it is to rebuild the pitches (Adams *et al.*, 2001). This is very expensive and beyond the means of most facilities or would be extremely damaging financially as a freshly laid pitch may require a “settling in period” of at least one season, depending on the depth of rebuild, reducing the capacity for games and potential revenue. Root breaks and layering have a number of causes, including poor rolling technique, top-dressing over thatch layers, and using topdressing soils that are incompatible with the resident pitch soil (i.e. the topdressing soil will not bind to the resident soil) (Shipton, 2008).

The existence of root breaks and layering is concentrated towards the centre of the profile with few within 30 mm of the surface and little below 100 mm with the majority at 50 mm depth (Figure 3.13). Shipton (2008) showed considerable horizontal displacement from rolling could be created down to 45 mm depth, possibly indicating the primary cause in this region. Adams *et al.* (2001) found horizontal breaks in the soil profile below 40 mm had a deleterious effect on the pace and bounce of pitches.

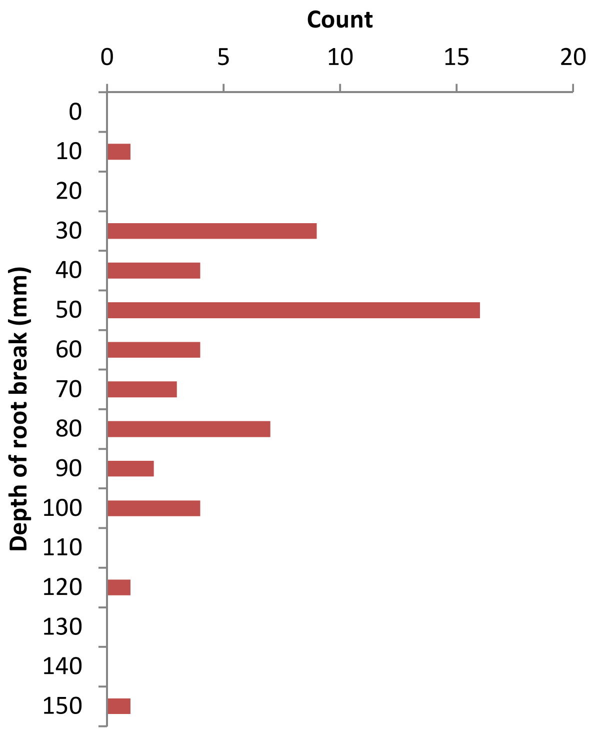


Figure 3.13 Reported depths of root breaks and layering in cricket pitches.

Much of the root breaks and layering may be a legacy of past management practises which with the adoption of modern management techniques will prevent the formation of further such problems, though this remains to be seen. Unfortunately this will not remove the breaks that exist already and little evidence exists beyond the anecdotal on how best to remove existing root breaks beside rebuilding. Aeration is often used to try and repair breaks. The general belief is that improving the rooting depth of the turf so that it bridges the break will hold the pitch together and aeration provides a route of least resistance to do this if the working depth of the treatment exceeds the depth of the break (Figure 3.14).

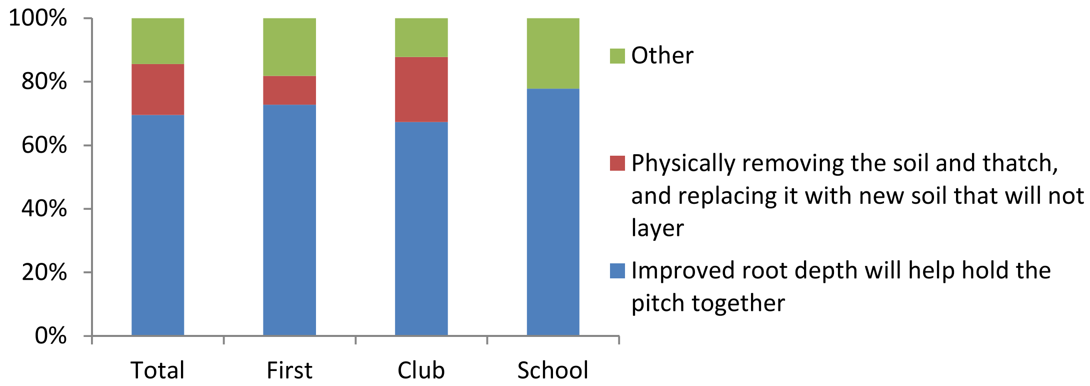


Figure 3.14 Aeration strategy goals used by Groundsmen for repairing root breaks and layering in cricket pitches.

The treatments chosen to solve this reflect this belief with the majority opting for deeper aeration techniques such as the deep drill and VOT. A minority of complete rebuilds and fraise mowing reflects the difficulties and expense associated with this strategy.

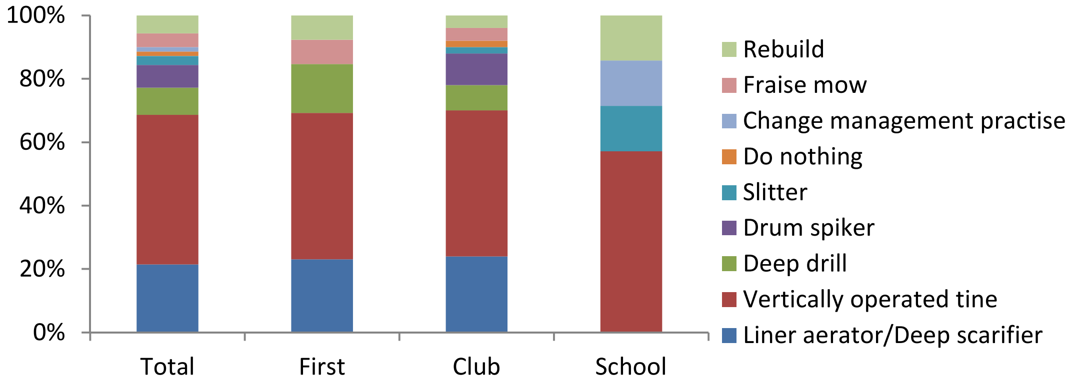


Figure 3.15 Equipment and strategies used to remove root breaks and layering.

3.3.6 Attitudes to aeration

Aeration is expected to play many roles in the upkeep of a cricket pitch. Groundsmen were asked a number of questions on the importance and benefits of aeration in aspects of cricket pitch maintenance (Figure 3.16 and Figure 3.17).

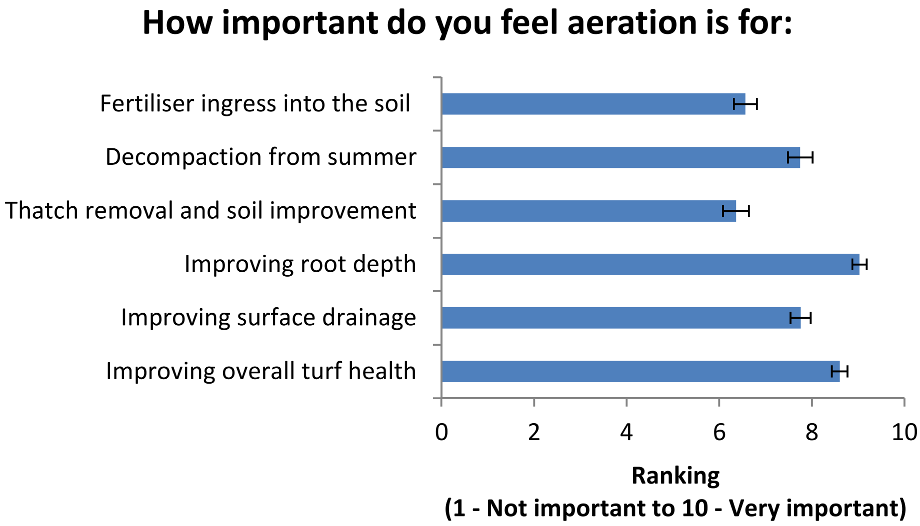


Figure 3.16 Groundsmans opinions of the importance of aeration for various factors. Scores are ranked on a scale from 1-10, when 1 is unimportant and 10 is very important.

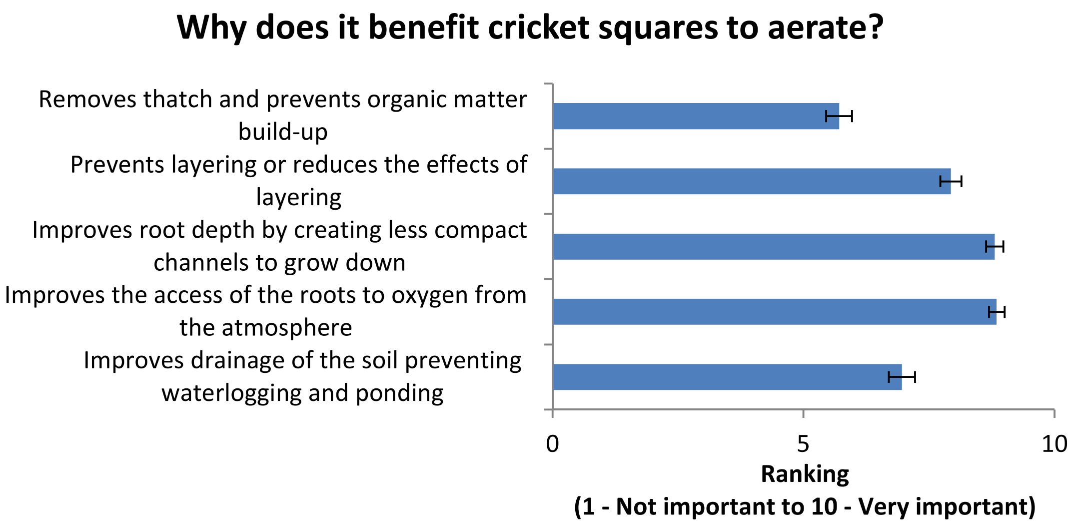


Figure 3.17 Groundsman opinions on the reasons for aeration treatments. Scores are ranked on a scale from 1-10, when 1 is unimportant and 10 is very important.

There were no significant differences in opinion between facility types except regarding decompaction from summer rolling where school groundsman ranked aeration at only 5.6 ± 1.0 out of 10 for importance relative to the club and first class groundsmen who ranked it at 8.0 ± 0.5 for importance. The large standard error in the school group indicates considerable variation in opinion. Overall aeration was considered as fairly important for all the processes queried, particularly for improving root depth and soil oxygenation.

3.4 Summary and discussion

The survey provides an outline of general aeration practises in cricket pitches in the UK. Patterns within the industry on aeration treatments were evident although a wide range of options both in machine type and application were noticed. The range in aeration practice reflects the lack of clarity in aeration effects and the broad expectations of groundsmen in what can be achieved with it.

Differences in aeration practice were noticed both within and between facility types indicating at all levels of the game a diversity of opinion and lack of centralised guidance coupled with the natural variability between every cricket pitch. Unlike rolling however, changing aeration strategies may require more than just a change in thinking and the frequency of application as each technique often requires a distinct piece of equipment representing a considerable financial barrier to change. The overwhelming majority use aeration as an annual treatment possibly leading to the conclusion that any aeration is better than no aeration accounting for the use of slitter type machines (though this could be due to a few brave experimentalists) and the widespread use of drum roller spikers that have long been associated with causing subsurface compaction. Guidance on the best practise of aeration, including abstaining, could improve pitch quality and maintenance efficiency by removing the dogmatic application with targeted action for specific purposes allowing tight resources to be allocated most effectively by only applying aeration with the right machine when it is needed. The VOT dominates as the treatment of choice invariably using solid tines hence much of the research and guidelines will be based around this technique.

Not only is aeration used as a regular preventative treatment but also as a cure for layering and root breaks. The extent of root breaks and layering in pitches at all levels of the game highlights a serious problem. Several reasons have been cited for root breaks and layering in pitches, and creating them can be avoided by following the appropriate guidelines (Adams *et al.*, 1994; ECB Staff, 2007; James and Shipton, 2009) however for the majority that already have them only two options exist: repair or replace. Aeration has been seen as a potential tool for repairing these breaks by increasing root depth to hold the layers together as well as penetrating through layers to replace or encourage mixing of the soil. Once more the need to address what aeration is for becomes important and its eventual aims when providing guidance to the industry. Essentially two sets of guidelines are required along with two sets of research. One to examine the use of aeration as an annual maintenance tool, and the second to examine aeration as a recovery tool for root breaks and non-binding layers. In this research the focus has been on aeration as a regular treatment although some elements of the research will obviously have implications for aeration as a layer-break recovery tool.

As a regular preventative treatment aeration is associated with numerous benefits for pitch improvement for which the majority of the evidence is purely anecdotal. Groundsmen generally consider aeration to be an important process in maintaining the vitality and functionality of the pitches they maintain, however little guidance and even less scientific evidence for the effective use of these machines on clay-based soils exists on which to base these opinions. As an example, control of organic matter is important in all natural turf sports surfaces, cricket being one of them. The widespread use of scarification as part of autumn maintenance demonstrates that within the industry this is a well-established rule, i.e. that groundsmen must take action to remove organic matter to prevent a deleterious build-up. Aeration is viewed as important to the control of organic matter through increased oxygenation aiding microbial breakdown. This is just one of the many expected benefits from aeration. The dearth of information shows a clear need to establish what effects aeration has and whether it is really conferring the benefits that groundsmen believe.

Aeration practices are varied, irregular and based on sales pitches and anecdotes. The creation of guidelines will establish aeration as a tool for achieving well defined goals from treatment rather than application in the wild hope that it will be a miracle cure for all the myriad problems created from attempting to grow deep rooting grass in soil conditions that encourage the very opposite behaviour.

4 Soil Shrink-Swell

Cricket pitches are primarily constructed from clay or clay loam soils. These soils exhibit shrink-swell behaviour. The shrink and swell of clay soils has been seen as one method of natural recovery for compacted soils by reducing dry bulk density and aiding the formation of stable soil aggregates (Grant and Dexter, 1990). The extent towards which the pitches can recover from the compaction effects of rolling and players (Section 1) by themselves is important in whether aeration is necessary, how much of over-winter recovery is due to shrink-swell rather than aeration, and how the two process interact. In a cricket pitch most of the effect of rolling is concentrated in the top 50 mm (Shipton, 2008). When soils swell, the greatest amount of swelling occurs when there is no overburden and diminishes as the burden is increased (Marshall *et al.*, 1996). Like rolling the effect of shrink-swell processes in the natural recovery of compacted soil is concentrated nearer the surface.

Crack formation in pitches affects the predictability of bounce and trajectory of balls rebounding from the surface and is thus important for health and safety reasons as well as for an enjoyable game experience. In the professional game an unsafe pitch would also have severe financial implications from cancelled games and a severely damaged reputation that may affect future earning potential. The extent to which crack formation is dependent on aeration determines when or if a certain treatment can be used. The crack formation characteristics would also be useful when choosing a soil for pitch construction, a tendency to from large cracks would be a bad characteristic, whereas, a pronounced level of self-amelioration would be of considerable benefit in terms of resources and maintenance.

4.1 Swelling

This experiment uses a modification of the Keen-Raczkowski (KR) method to measure shrink and swell in four soils. Time-lapse photography (TLP) was used to measure the real-time volumetric expansion of the soils over time. The results of the TLP method were then compared to the standard KR method.

The TLP method provides all the information of the KR method as well as providing a record of expansion over time, elucidating further behavioural characteristics. Air entrapment caused significant swelling in all soils except in a coarse sand soil. Soil swelling was proportional to clay content. Two stages of expansion were demonstrated for soils with clay contents ≥19.9%.

4.1.1 Introduction

The processes driving soil swelling are numerous and subject to some debate. Generally soil particles can be considered as hydrophilic solids. The extent of swelling exhibited by soils is a balance of adsorption attraction, interparticle attraction and compressive weight (Parker, 1986). The swelling of clay soils occurs in two stages. The first stage is driven by the attraction between water molecules and polar groups, charge sites and exchangeable ions bound to the soil surface (Marshall *et al.*, 1996). Uncharged surfaces attract water molecules through weak intermolecular forces: van der Waals, dipole-dipole, and hydrogen bonding. Generally these forces decay rapidly in strength with distance but for a surface containing many atoms this decay can be reduced from a sixth power dependency to a third power dependency (Parker, 1986). Charged surfaces generally arise from structural defects in the mineral lattice. The surface charge is balanced by electrostatically bound counterions. As with free ions in solution the counterion and charge site hydration is driven by ion-dipole interactions and ion-induced dipole interactions with water molecules – generally, the higher the charge density the greater the energy of hydration. Charged surfaces have much greater hydration energies than uncharged surfaces, hence clays are much more hydrophilic than sands and silts as clays are will tend to have more structural defects due to their mineralogy (Parker, 1986).

For phyllosillicate clays intercalation of water between layers leads to a process called crystalline swelling. Crystalline swelling is controlled by the balance of attraction between clay layers (from coulombic and van der Waals interactions) and repulsion (from hydration of interlayer ions and surface charge sites) (Laird, 1996). Two other theories regarding interlayer swelling are osmotic swelling and long-range water particle interaction. Osmotic swelling theory is based on the principle that the bound counterions near the surface create the effect of a semi-permeable membrane generating a concentration gradient down which the water will diffuse, like osmosis. Studies suggest however that this alone would not be sufficient to explain the level of swelling observed. Long-range water particle interactions occur when water molecules close to the surface become structurally strained to fit the surface; the deformations induced are carried back through the water increasing hydrogen bonding thereby attracting more water and increasing swelling. The efficacy of long-range water particle interactions is also debated with estimates of these structural effects only occurring over 2-7 molecular layers of water (Parker, 1986).

The microstructure of clays will also affect swelling. Different arrangements of clay domains can both inhibit and assist swelling. Edge-to-face bonding will inhibit expansion as in order to expand the edges must break with the face. In contrast edge-to-edge bonding can increase swelling as one clay mineral can force its bonded partner's layers further apart as it swells (Rowell, 1965).

Macroscopic factors affecting expansion include capillary phenomena and entrapped air in the soil (Parker, 1986; Taboada *et al.*, 2001a; Gäth and Frede, 1995b). Swelling via air-entrapment requires the build-up of air pressure trapped ahead of a wetting front. The process of air-entrapment in unsaturated soils is poorly understood despite significant research as it is a complex process with a very broad combination of factors (Wang *et al.*, 1997; Taboada *et al.*, 2001a). Parker *et al.* (1980) found an inverse relationship between swelling and pore size; smaller pores present more resistance to air-flow so require a higher pressure to drive the air out. Given a free supply, water flows quicker in larger pores than smaller according to the Hagen-Poiseuille equation. If the small pores are in contact with the larger ones the water will, when it reaches the junction of a smaller pore, flow into the smaller pore and enclose the air. The compression of the trapped air will be close to the capillary pressure, so smaller pores will exert a greater pressure. Swelling due to air entrapment is really a process of inflation (Gäth and Frede, 1995a).

Capillary cohesion occurs between soil particles connected by a thin film of water - the smaller the particles, the more effective the cohesion. As water concentrations increase capillary cohesion will at first increase until it peaks when the maximum air-water interface is achieved; with further addition of water cohesion is reduced.

Soil shrinkage and swelling properties are primarily described by measuring the shrinkage properties of the soil despite big differences between the two processes as it is generally easier to measure and control shrinkage (Grant, 2008). This experiment examines the swelling properties of five different soils. Using a simple method with minimal measurement equipment – a camera and a computer – the experiment captures dynamic swelling processes of unburdened air-dry samples.

4.1.2 Materials and methods

Six soils were used in the experiment: clay (C), Boughton County™ (BC), Ongar™ Loam (OL), sandy clay loam (SCL), sandy silt loam (SZL) and sand (CS). Soil BC and Soil OL are both commonly used in the construction of cricket pitches in the UK. The bulk and clay fraction mineralogy of the four soils were determined by x-ray powder diffraction (Table 4.1). The water release characteristics of each soil were determined using sand tables and pressure cells at nine suction pressures. Due to the homogenous nature of the prepared laboratory soils an accelerated process for water release was used.

Table 4.1 Analysis of soils used

Properties	Soil type					
	Clay	*Clay Loam*	*Clay Loam*	*Sandy Clay Loam*	*Sandy Silt Loam*	*Sand*
	Soil code					
	C	BC	OL	SCL	SZL	CS
Grain size						
Coarse sand (0.6mm - 2mm) (%)	3.7	1.7	1.7	3.4	0.2	87.4
Medium Sand (0.212mm - 0.6mm) (%)	18.6	17.3	12.9	32.8	2.3	11.4
Fine sand (0.063mm - 0.212mm) (%)	6.5	17.0	12.1	24.6	46.9	0.6
Total Sand (2mm - 0.063mm) (%)	28.8	36.1	26.7	60.9	49.4	99.4
Silt (0.002mm - 0.063mm) (%)	24.0	29.9	43.2	19.2	49.8	0.6
Clay (<0.002mm) (%)	47.2	34.1	30.1	19.9	0.8	0.1
Whole soil quantitative mineralogical analysis						
Quartz	42.4	52.1	58.7	72.5	100.0	—
Plagioclase	2.4	3.4	4.1	2.1	0.0	—
K-spar	3.9	5.5	5.3	3.2	0.0	—
Calcite	3.8	1.5	2.4	0.5	0.0	—
Goethite	4.5	6.7	3.7	6.0	0.0	—
Anatase	0.2	0.3	0.2	0.2	0.0	—
Mica/illite	6.9	4.8	2.6	3.4	0.0	—
I/S	28.6	19.3	19.7	10.1	0.0	—
Kaolinite	7.3	6.5	3.3	2.1	0.0	—
Relative percentage of clay minerals in clay size fraction						
Kaolinite	10	15	10	11	55	—
Mica/illite	6	10	9	7	13	—
Illite-Smectite	85	75	81	82	32	—
% smectite layers	50-60	50-60	50-60	50-60	50-60?	—

4.1.2.1 Sample Preparation

The soils were packed in boxes according to a modified Keen-Raczkowski method (Keen and Raczkowski, 1920). A box consists of a hollow brass cylinder (55.5 mm internal diameter, 26.5 mm height) open at the top with a perforated brass base. Each box was carefully weighed (±0.0001 g) and the internal dimensions measured before use. A filter paper was placed at the bottom of each box so as to completely cover the base. Each soil came from a single source, and sieved to 1 mm. Soil was added gradually whilst gently knocking the box to ensure an even distribution. When filled, the excess soil was scraped off using a palette knife level with the top of the box. The soil was then gently agitated to encourage settling by tapping around the outside of the box. More soil was then added, the surface levelled and the process repeated until there was no further change in surface level due to settling of the soil. The filled box was then weighed.

Each box was fitted with a scale bar positioned 4 mm below the top and placed in an empty petri dish. The camera was positioned to take photos in a single plane of the packed box (Figure 4.1)

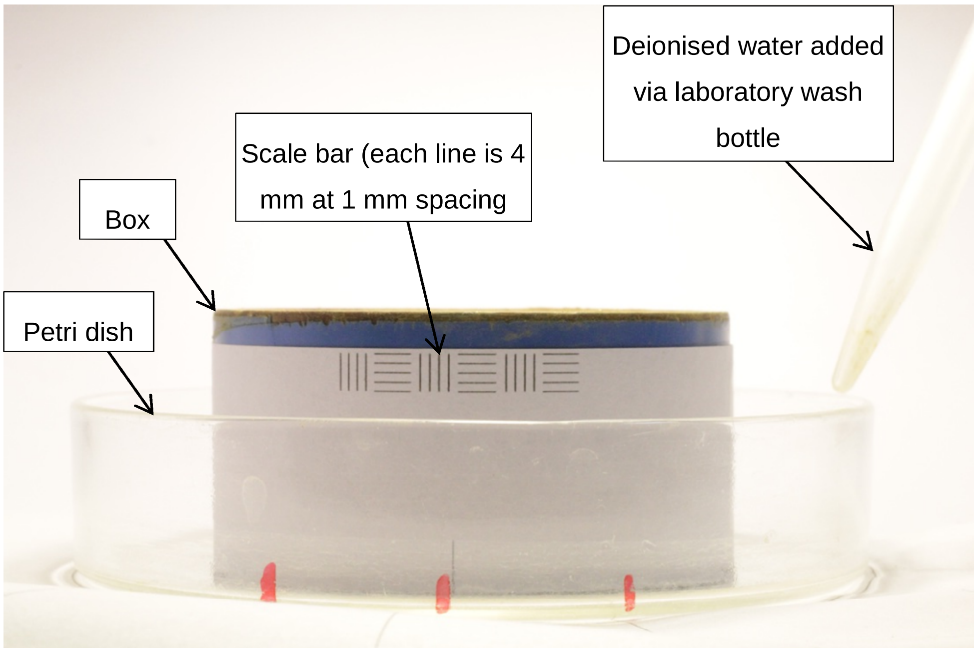


Figure 4.1 Captioned sample photograph from the time-lapse images of a prepared box just prior to the initial addition of water.

4.1.2.2 Mass based analysis (KR method)

After 48 h the boxes were removed from the tray and processed as per the Keen-Raczkowski method. This method approximates the volumetric expansion of the soil by using a mass comparison method. The surplus soil is removed, dried and weighed and compared to the dried mass of residual soil remaining in the box. As the box volume is known it is possible to calculate the average bulk density of the residual soil. Dividing the mass of surplus soil by the dry bulk density of the residual soil gives an approximation of the volume of the expansion by assuming a uniform bulk density throughout both the residual and surplus soil.

4.1.2.3 Time-lapse analysis (TLP method)

Images were recorded using a EOS 550D (Canon, Tokyo, Japan) with a 50 mm F2.8 EX DG Macro lens (Sigma, Kanagawa, Japan) mounted on a tripod (Manfrotto, Cassola, Italy) with the box and petri dish were centred on the optic axis. Camera settings and properties are listed in Table 4.2

Table 4.2 Camera settings for image capture.

Property	Details
F-stop	f/20
Exposure time	1/30 s
ISO speed	3200
Focal length	50 mm
Subject distance	400 mm

The time intervals between photographs were 5 seconds for the first five minutes, 20 s for the next 55 min and 10 min for the next 47 h. The water level in the tray was filled to maximum at 10 s, 30 min, 15 h, 24 h and 45 h after photographing had started. Initial pilot measurements determined swelling as a non-linear process with a rapid initial phase requiring a high initial frequency that reduces over time and can be captured by a lower frequency of images to minimise computational time in image processing.

The time-lapse photographs were processed using Matlab (Mathworks, US) which counted the number of pixels through which the soil had risen over time and compared it to the width of the box thus allowing the calculation of volumetric expansion with time (Figure 4.2). The use of the scale bar was too complicated due to the curvature of the box and its location forward of the focal plane of the image thus it was underestimating the shrinkage as the scale bar was too large in comparison to the soil. Though this could be compensated using focal length and distance to object the use of the box width was considered easier and more accurate. Soil expansion, like soil shrinkage, was assumed to be rotationally symmetrical (Grant, 2008). To study the validity of the assumption of rotational symmetry the left and right hand side of each image were compared and the mean percentage difference of the two halves (compared to total number of pixels) was recorded. From the photo data two key parameters were recorded, the expansion after 250 min (designed to capture the magnitude of initial rapid swelling) and the expansion after 48 h (maximum end-point swelling).

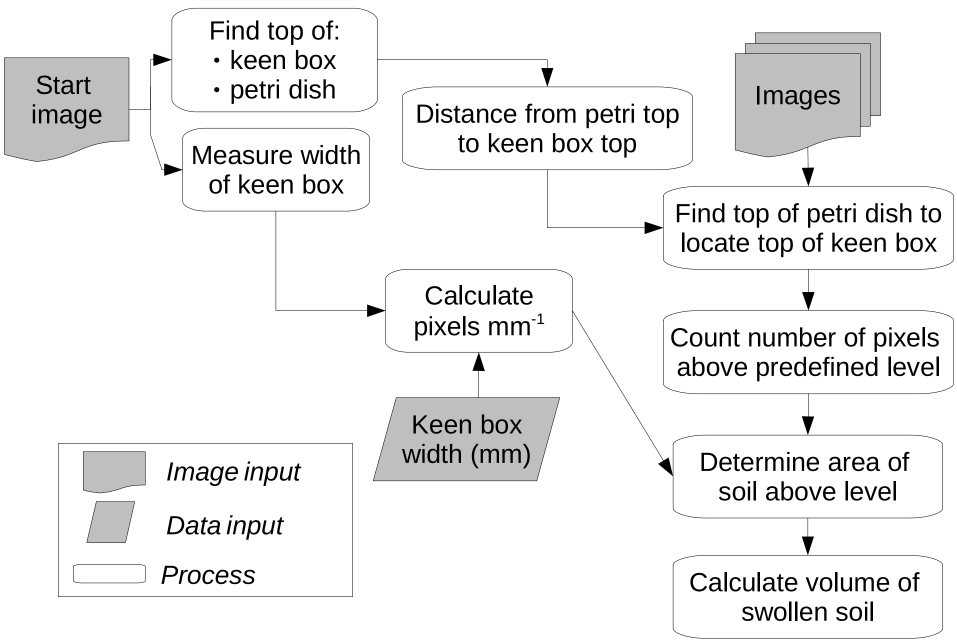


Figure 4.2 Flow chart of the analysis programme

A typical computational time for processing an entire 48 h run of images was approximately 45 min. Three replicates of each soil were tested and the average swelling over time computed.

Soils BC and OL did not reach equilibrium after 48 h and so one additional sample of each soil was run over an extended period of seven days.

4.1.3 Results

4.1.3.1 Method Comparison

Plotted histograms and normal P-plots showed both the KR data and TLP data can be approximated to a normal distribution (n=24). The results were fitted to a 1:1 line (Figure 4.3, adjusted-r^2=0.97, RMSE 1.78). A matched-pairs t-test gave the average difference between the two methods as 0.33% (S.E. 1.65); the two populations were not significantly different (p=0.34).

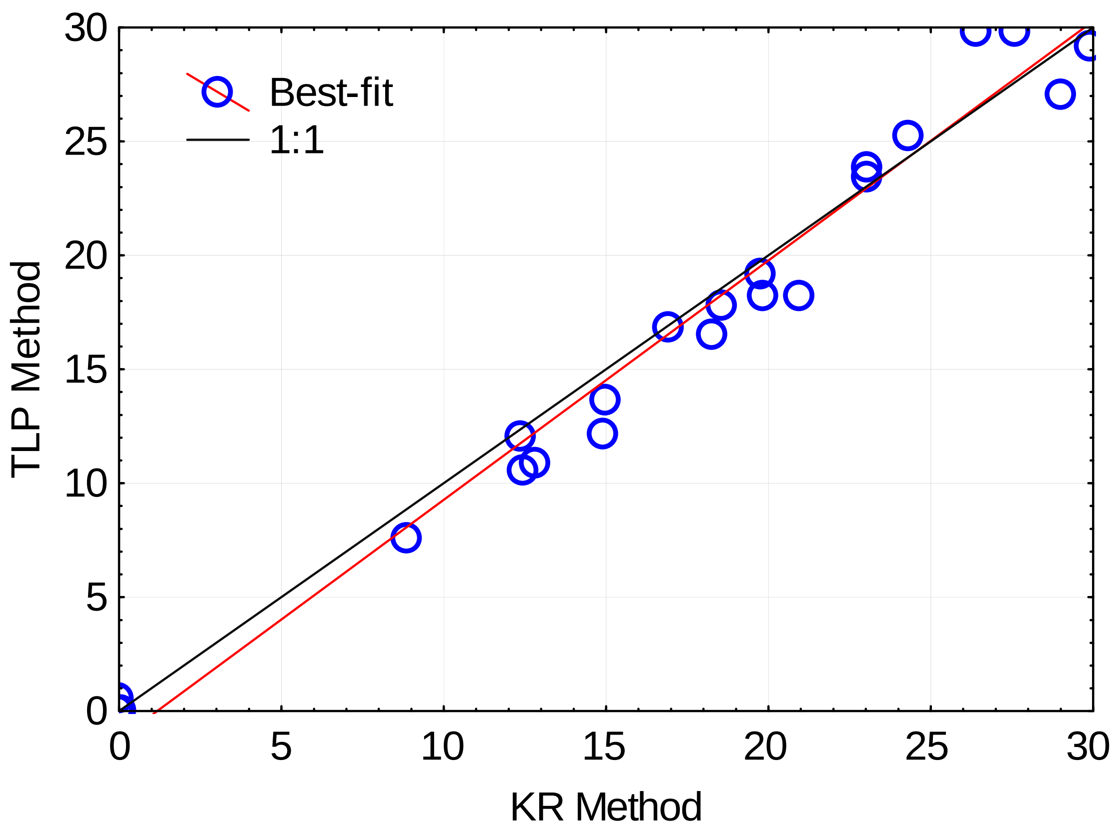


Figure 4.3 Comparison of KR and TLP method results. Adjusted-r^2=0.97, RMSE 1.78.

Image asymmetry was low for all soils except the coarse sand. Negative values correspond to a larger volume of soil on the right hand side; positive values correspond to a larger value on the left hand side of the image (Table 4.3). None of the soils (including the coarse sand) showed a significant difference from zero ($p<0.05$) for asymmetry. The large values exhibited by the coarse sand are a result of the extremely low number of pixels in the image due to the lack of swelling thus any imbalance is proportionally much larger.

Table 4.3 TLP method results

Soil	Expansion after 250 min (%)		Expansion after 48 h (%)		Image asymmetry (%)	
	Mean	S.E.	Mean	S.E.	Mean	S.D.
C	26.94	0.21	30.22	0.19	-1.44	2.18
SCL	10.26	0.34	15.13	1.56	-1.36	10.10
BC	17.87	0.34	24.77	0.47	-2.33	3.13
SZL	10.35	0.67	11.13	0.44	0.85	2.25
CS	0.07	0.01	0.03	0.01	61.03	67.49
OL	9.14	0.06	18.67	0.46	1.41	2.19

4.1.3.2 TLP soil swelling

The results in Table 4.3 are exclusively from the TLP method. The coarse sand exhibited almost no discernible swelling. All other soils exhibited considerable swelling (Table 4.3).

The sandy silt loam exhibited a discontinuity when the petri dish water levels were refilled after 30 min (Figure 4.4). Similar but much smaller effects were observed for the other soils where water refills were followed by slightly altered rate of expansion in the individual results. During late-stage swelling watering events sometimes preceded a collapse of swelling volume. The process of averaging the three trials for each soil removed most of these features.

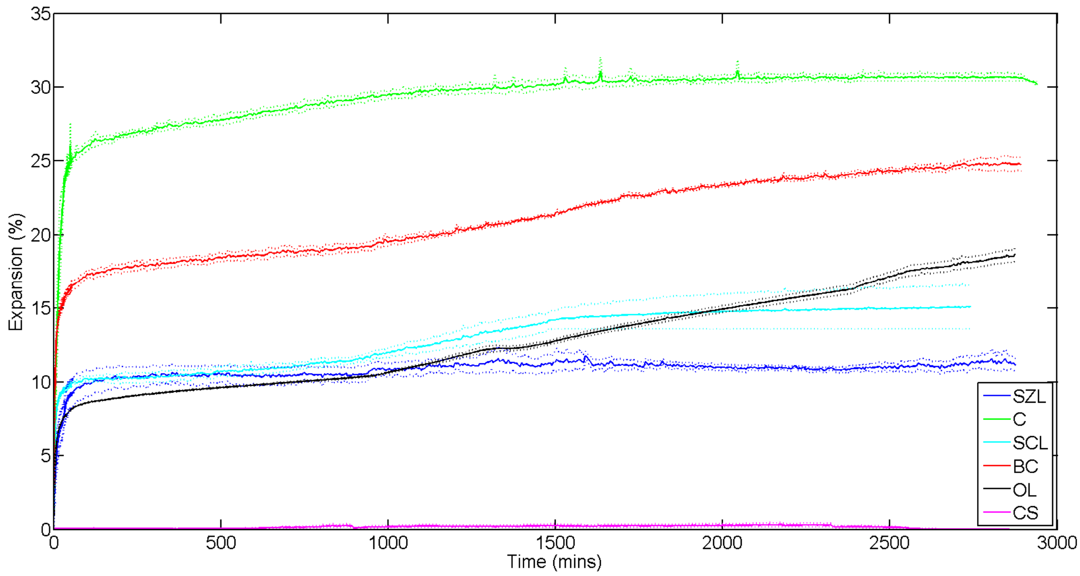


Figure 4.4 Mean percentage expansion of the the three replicates of each soil with time. Dotted lines indicate standard error. Soil C is the clay soil, Soil BC is Boughton County™ (clay loam), Soil OL is Ongar™ Loam (clay loam), Soil SCL is sandy clay loam, Soil SZL is sandy silt loam, and Soil CS is the coarse sand.

The coarse sand (Soil CS) did not exhibit any swelling.

The sandy silt loam (Soil SZL) (ignoring the discontinuity from watering) shows swift initial expansion within the first 60 min which then rapidly declines giving an expanded soil volume that remains approximately constant. This is a one-stage expansion process.

The remaining four soils appear to follow a two-stage expansion process. The first stage consists of rapid expansion usually ending within the first hour after expansion has started, like soil SZL. The expansion rate tails off into a period of low to zero expansion of varying duration depending on soil. The second stage of expansion occurs at a much lower rate than the initial stage and eventually tails off once the maximum expansion is reached. The times at which the stages begin and end are different for each soil and appear to occur more quickly for the sandy loam than the clay loams or clay. It is possible that the clay soil did not achieve equilibrium, though the rate is declining, the two clay loams, BC and OL, clearly did not achieve maximum expansion in the initial 48 h. The two-stage expansion is much more evident when the time is plotted on a log scale (Figure 4.5).

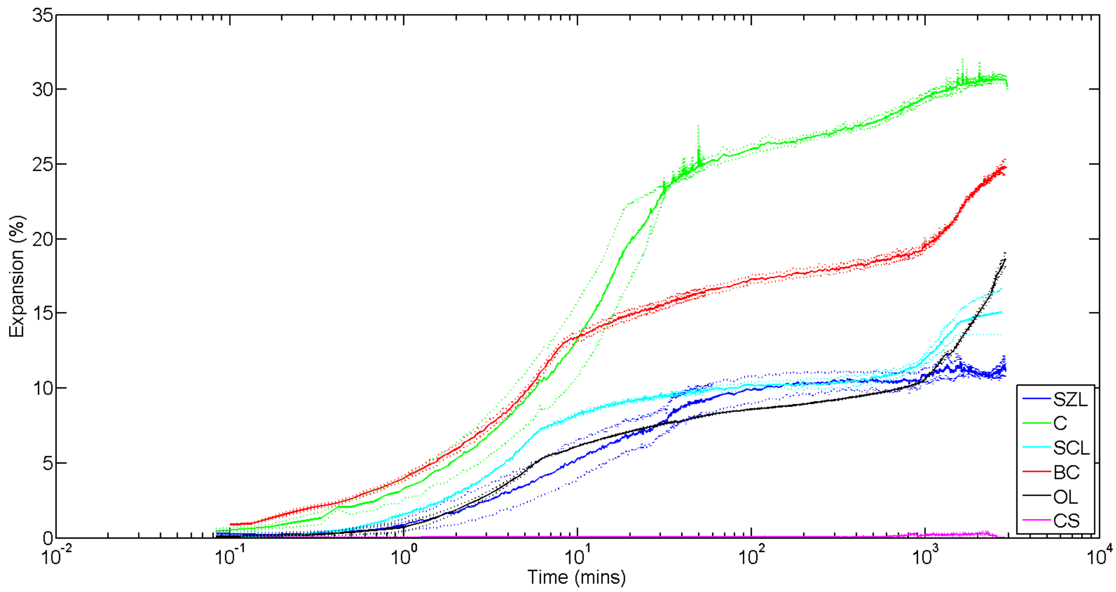


Figure 4.5 Mean percentage expansion of the the three replicates of each soil with the nautral logarithm of time. Dotted lines indicate standard error. Soil C is the clay soil, Soil BC is Boughton County™ (clay loam), Soil OL is Ongar™ Loam (clay loam), Soil SCL is sandy clay loam, Soil SZL is sandy silt loam, and Soil CS is the coarse sand.

In the extended trials of BC and OL the rate of expansion in the third stage declines very slowly so it is very difficult to pinpoint when equilibrium has been reached as the soil still continues to swell, albeit very slowly (Figure 4.6). Soil BC seems to reach maximum expansion of 29.2% after about 8000 min (~5.5 days), Soil OL was assumed to have reached maximum expansion (27.01%) when the soil volume dropped precipitously after 7 days, up to that point it had still been expanding. The drop in the recorded expansion followed a collapse of the soil, potentially due to the escape of entrapped air. Unfortunately there were no replications of the extended trials but it is hypothesised that the replications would follow closely the curves below given the excellent repeatability of the 48 h trials. The drop at the end may be a unique feature of that particular box so any future experiments may not show a distinctive slump as seen here as each packed box will not have the exact same pattern of structure and may entrap air or collapse at different points but the overall trend should be the same.

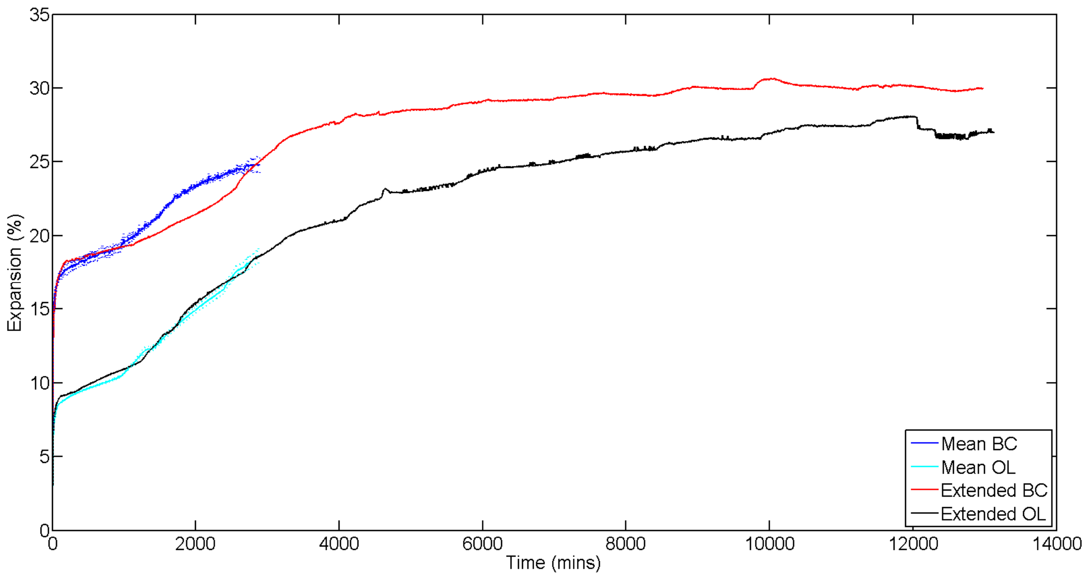


Figure 4.6 Mean percentage expansion of the the three replicates and the recorded expansion from the extended trials of Soil BC and Soil OL with time. Dotted lines indicate standard error. Soil BC is Boughton County™ (clay loam), Soil OL is Ongar™ Loam (clay loam).

4.1.4 Discussion

4.1.4.1 Method Comparison

The excellent one-to-one correlation of the results from each method clearly shows the effectiveness of the TLP method as equal to the KR method. The TLP method also provides valuable insight into the behaviour of the soil as it expands; providing a much more informative dataset than by the KR method alone as it yields time-series data on the extent of swelling over time allowing greater insight into the dynamic process of soil swelling rather than just a single value end-point.

The assumption of rotational symmetry appears to be vindicated by the excellent correlation with the KR method and the low asymmetry of the images examined. Further testing for each soil is needed before this can be tested robustly. The addition of a second camera imaging a perpendicular section would provide a much better conversion of the two-dimensional images to approximate the full three dimensions of the actual object as it would rely on symmetry over only a quarter of a rotation as opposed to a half. Further enhancement of the image filters and modifications of the apparatus to reduce background noise would greatly reduce the variation in the TLP method such that the accuracy could well be much greater than that of the KR method (Table 4.4). The very large value the error associated with Soil CS using the TLP method is due to the negligible level of swelling relative to the background noise of the images. For the remaining five soils all the recorded standard errors of the TLP method were lower than the KR method except Soil SZL where it was marginally greater.

Table 4.4 Listing and comparison of the standard error of the end-point swelling for each soil measured using the Keen-Racszowski (KR) method and time-lapse photography (TLP) method.

Soil	KR Method	TLP Method	TLP error as percentage of KR error
C	1.24	0.78	63
SCL	1.14	1.12	98
BC	1.62	1.32	81
SZL	0.93	0.96	103
CS	0.01	0.18	2040
OL	2.43	2.18	90

Results from the TLP method are analogous to those obtained for the free-swell of soils used in other studies (Basma *et al.*, 1996; Al-Zoubi, 2008) but as the measurement is remote from the soil there is no interference from the equipment unlike using an odeometer where the measuring equipment rests on the surface of the soil and must in some way impede it.

4.1.4.2 Real-time unburdened soil swelling

Soil CS exhibits almost no swelling, if any. This is partly due to a complete absence of swelling clay minerals, though this cannot be the only reason as the

Soil SZL also has no clay content. The particle size distribution of Soil CS is dominated by large sand particles resulting in a large average pore size (Figure 4.7). Large pores have smaller matric potentials and relatively weak interparticle attractions due to small contact surface area resulting in generally weak long-range interactions (Parker, 1986).

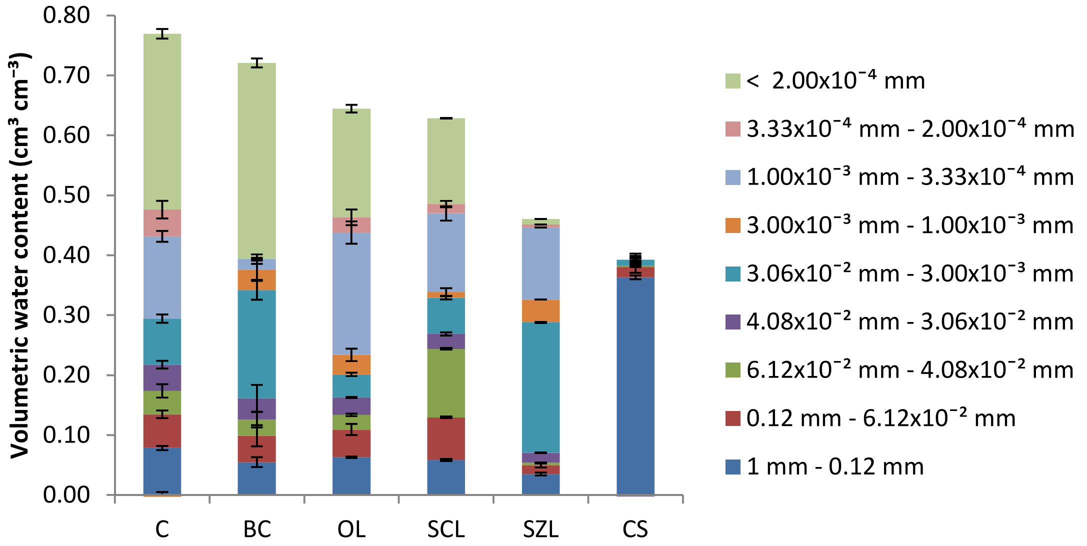


Figure 4.7 Pore space distribution of the soils. Soil C is the clay soil, Soil BC is Boughton County™ (clay loam), Soil OL is Ongar™ Loam (clay loam), Soil SCL is sandy clay loam, Soil SZL is sandy silt loam, and Soil CS is the coarse sand. Vertical bars denote standard error.

All soils exhibiting significant end-point swelling (SZL, C, SCL, BC and OL) show an initial rapid expansion, which declines and ceases before 250 min of swelling have occurred. Despite differing end-points and rates the general shape of the curve up to 250 min is the same for all swelling soils possibly indicating a common mode up to this point. Soil SZL has no expanding-clay content so expansion cannot be clay driven in this soil. A potential mechanism for zero-clay expansion is entrapped air in the soil (Parker, 1986; Taboada *et al.*, 2001a; Gäth and Frede, 1995b). In soil CS the large pores present little obstacle to both air and water flow, the limited distribution of pore sizes leading to a uniform wetting front driving the air from the soil as it progresses through the soil leaving no entrapped air pockets as well as allowing easier escape of the air were it to be trapped. In contrast in Soil SZL the finer sand and silt particles create a smaller average pore size and a greater range of pore sizes leading to a heterogeneous flow of water through with the potential for increased air entrapment as a consequence.

When water was added to the petri dish at timed intervals, to replace that absorbed by the soil or evaporated, the general trend of the expansion curve was altered for each of the soils. This is easily solved by using a constant-head water reservoir in the experiments and is a recommendation for any future work as it should maintain a constant pressure of water. For the most part these changes were small and, when the results were averaged, disappeared. The most noticeable of these changes, and one that remains clearly visible, is in the sandy silt loam (SZL). Specifically it is the watering at 30 min that causes the discontinuity. The water refill increases the level of freely available water and raises the pressure of water outside causing flow into the soil. The corresponding effect on swelling is then caused by increased pressure on the already entrapped air or it causes flow into previously unsaturated regions entrapping more air.

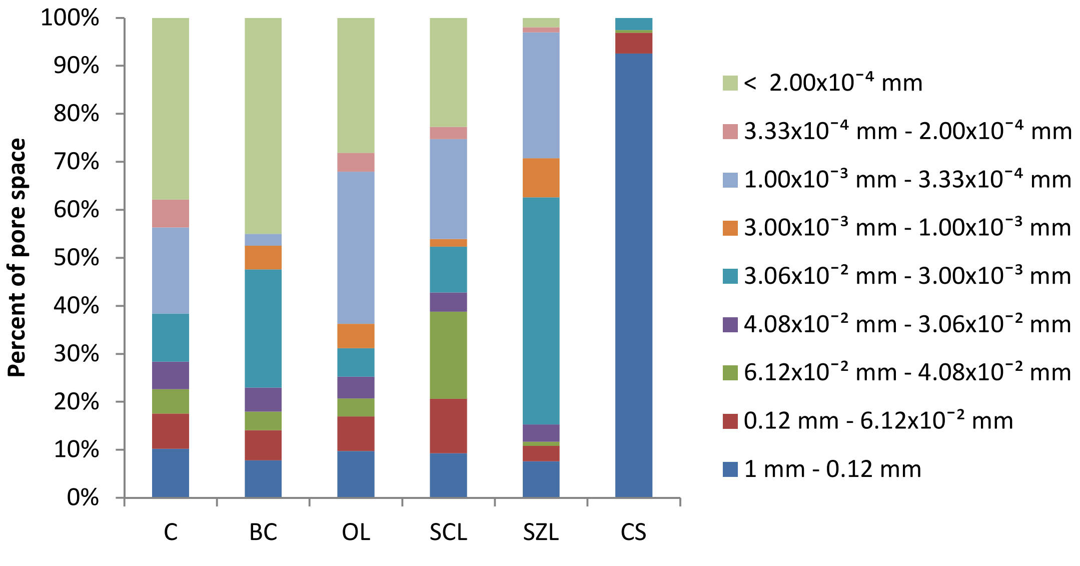


Figure 4.8 Pore size distribution as a percentage of total pore space for each soil. Soil C is the clay soil, Soil BC is Boughton County™ (clay loam), Soil OL is Ongar™ Loam (clay loam), Soil SCL is sandy clay loam, Soil SZL is sandy silt loam, and Soil CS is the coarse sand.

All the soils that exhibited swelling have heterogeneous pore size distributions. Notably Soil CS has almost no pore space outside of the 1-0.12 mm pore diameter range and exhibited zero swelling. For the remaining soils it can be seen that there are categories where there is a large volume of pore space interspersed with pore diameters where there is little or no pore space of that size. (Gäth and Frede, 1995a) stated that a heterogeneous pore size distribution is a requirement for air entrapment. The extent of initial stage swelling is possibly related to the amount of pore space below $2x10^{-4}$ mm (Figure 4.8). Soil BC and C having the most amount of pore space in this category show the greatest initial swelling, Soil SCL and Soil OL both have lower amounts and show a consequently lower level of swelling. There are two exceptions to this theory:

- Soil C and Soil BC. Soil C has a lower volume of pores of diameter <200 nm than Soil BC yet exhibits greater initial swelling.
- Soil SZL has almost no pores in this region of size and exhibits as much swelling as Soil OL and Soil SCL (in the initial phase).

The amount of swelling via air entrapment is inversely proportional to pore size (Parker *et al.*, 1980), possibly Soil C has a higher volume of smaller pores than Soil BC that cannot be resolved via the method used leading to greater swelling as well as a greater clay content which would naturally lead to an expected larger swelling.

Soil SZL being composed almost entirely of quartz will have very weak interparticle attraction and little or no cohesive materials binding the soil particles together, thus allowing a correspondingly greater amount of swelling despite the larger pore sizes which should lead to reduced swelling. Alternatively it is related to an optimum pore size distribution, requiring sufficiently narrow pores to drive significant upward movement of water yet a variety of pore sizes to ensure heterogeneous water movement and consequently air entrapment. If the pore space is dominated by small pores this would restrict hydraulic conductivity through increased resistance to flow so the soil would saturate more slowly and less air would be captured. No clear pattern in the pore size distributions is evident to support this theory

It is an inescapable fact that the pore size distribution is related to the particle size distribution in that soils with a high proportion of clays are far more likely to have a greater proportion of smaller sized pores. Thus the link between initial swelling and pore size distribution could merely be linked to clay content. However, Soil BC and Soil OL have quite similar clay contents and very similar illite/smectite contents (19.7% and 19.1% of total respectively) (Table 4.1) so if the swelling in this initial phase was primarily clay-mineralogy driven the two soils would be expected to show similar trends, which they clearly do not (Figure 4.6). It is proposed that initial expansion consists of both a mineralogical driven expansion and air entrapment and that the two processes occur at the same time (Bonneau and Levy, 1982) and are linked. Entrapped air has long been known to cause the breakdown of aggregates as they rupture under the pressure of the compressed gas (Gäth and Frede, 1995a; Grant and Dexter, 1990). Clay soils expand in two stages, the hydration of attached ions, followed by osmosis-like diffusion of water between the layers (Marshall *et al.*, 1996). The ions bound to the surface cannot move freely in solution and so create a concentration gradient analogous to as if they were contained behind a membrane so water diffuses down the concentration gradient rather than due to the hydration potential of the ions. When the water is added to the clayey soils, the clays within start to swell as the first stage of hydration begins, interparticle cohesive materials are dissolved or weakened reducing restrictive forces, and air is entrapped in the pore network. The entrapped air causes aggregates to rupture exposing more clay surface for hydration, which in turn causes more swelling, one process feeding the other (Grant and Dexter, 1990; Bolt and Koenigs, 1972). The two stage swelling process can be interpreted with this information in several ways. No information was available on the time scales of the two clay hydration processes but the simplest explanation is that the rapid first stage swelling consists of a combination of air entrapment, aggregate breakdown, and first stage clay swelling, followed by slower osmosis driven swelling as the second stage.

Alternatively, the initial stage swelling consists of air entrapment and the first stage of swelling with a lull as these processes are complete. As the soil becomes more moist the soil strength decreases causing the compressed air to start rupturing the pores that enclose it increasing the surface area and exposure of expansive clays so causing further first stage clay hydration and swelling, which causes the increase in swelling rates which marks the start of the second stage swelling process. The remaining swelling is then osmosis driven, slowly approaching the maximum swelling size.

The two cricket loams, Soil BC and Soil OL, showed very different behaviour. Both soils contain approximately equal amounts of swelling clays (19.7% and 19.1% of bulk respectively). Soil BC achieves the majority of its expansion in the initial phase whereas Soil OL shows much less expansion in the first phase with the majority of overall expansion in the second phase. The exact mechanism is beyond the scope of this experiment but the pore size distribution of Soil OL is more similar to Soil SCL, whose behaviour it mimics in the initial phase of expansion, than Soil BC. Soil BC consists of a large proportion of very small pores ($<200\text{x}10^{-4}$ mm) but has relatively little volume of pores in the next three categories of pore size from $3.06\text{x}10^{-2}$ – $2.00\text{x}10^{-4}$ mm. The distribution of pore size in Soil BC weighted towards each end of the size spectrum could lead to a situation of rapid water movement through the larger pores leading to a greater volume of air entrapment in the large volume of very small pores and a consequently greater initial swelling than the more evenly distributed pore sizes of Soil OL.

4.1.4.3 Method limitations and future work

Expansion of this technique is limited only by ingenuity and as always money. The addition of extra cameras taking pictures simultaneously from multiple angles would improve accuracy by only requiring an assumption of rotational symmetry over 90° instead of 180° as well as providing another useful check on rotational symmetry by comparing the soil in two separate planes.

The natural expansion of the current method would be to examine structured soils and the effects of fast and slow wetting.

A constant head water reservoir rather than the periodic replenishment of the water would eliminate “bumps” in the soil curve. Slow wetting trials are also suggested to assess the effect of purely mineralogical swelling as slow wetting will drastically reduce any air entrapment (Gäth and Frede, 1995a). Ideally the results for each soil would present soil swelling against soil water content. If a constant head water reservoir was used the volume of water outside of the keen box would be constant. If the experiment was conducted on a mass balance then the weight could be recorded simultaneously and the weight of water outside of the keen box could be accounted for and the gravimetric water content calculated, similar to the Shrinkage experiment (Section 4.2).

To represent more truly cricket pitch conditions it is recommended that the experiment be scaled up in size and the soil wetted from above under simulated irrigation (fast wetting) and under simulated rainfall (slow wetting).

4.1.5 Conclusions & relevance to research

The main aim of this experiment was to prove the effectiveness of the time-lapse method for monitoring soil swelling. The method successfully monitored soil swelling over an extended period of time, elucidating individual swelling curves for each soil with a high degree of repeatability. The end-point swelling results compared excellently to the established KR method. The validity of the rapid wetting method used in both experiments is questionable given the level of air entrapment this causes. It is likely the swelling results would have been very different if the wetting had occurred slowly. To truly characterise the behaviour of a soil both slow and fast wetting should be analysed as both can occur in the real world: slow wetting as a steady drizzle of rain and fast wetting as a period of heavy irrigation. Often cricket pitches are subjected to heavy irrigation where Groundsmen saturate the pitch after a match ends to aid recovery of the grass and help new seed to germinate. It is likely under these conditions that air entrapment effects will occur.

The experiment examined a variety of soils; each soil was different in its response to water addition. For soils containing a significant proportion of swelling clays a two-stage swelling process was evident consisting of a combination of both air entrapment and mineralogical swelling of the clays as the root cause. For soils with zero clay content the amount of swelling was dependent on pore size. Soil CS with a narrow pore distribution and large average pore size showed negligible swelling. Soil SZL had a broader pore size distribution consisting of numerous small pores and exhibited significant swelling, but in a one stage process.

Soil BC and Soil OL despite similar clay contents showed disparate behaviour due to dissimilar pore size distributions. In terms of ameliorating the negative effects of compaction it is unclear as to which soil would be best. (Grant, 2008) attempted to quantify the effects of air entrapment and soil swelling on soil amelioration. They concluded that generally air entrapment alone was not sufficient to ameliorate the compaction in the samples. Differential swelling of clays was sufficient to cause some improvement but the effects were much stronger when both processes were combined, the whole being greater than the sum of its parts. Soil BC which shows a greater initial phase of swelling, indicating greater air entrapment and mineralogical swelling, so is more likely to be self-ameliorating. This is important for choosing soils for constructing pitches as it should allow for the easier maintenance of the pitch if the soil itself can relieve some of the compaction over time allowing for better turf grass growth.

Aeration aids infiltration by creating macropores which also act as small reservoirs capturing surface runoff. Increased water content causes increased swell, particularly if the pitch can be wetted quickly to increase air entrapment. Generally most aeration occurs after the pitch has already wetted sufficiently for the soil to become soft and pliable, when the weather is usually wetter, around late October (Section 3). The maximum amount of swelling is achieved by wetting a dry soil up to saturation, adding water to a partially swollen wet soil will be less effective in soil compaction amelioration. Thus the benefit of water capture and infiltration from aeration is already partly negated. Ideally a balance between soaking the pitch to gain the maximum swelling via air entrapment but also allowing it to drain so as not to drown the grass roots and create an anoxic environment is what is required. The most benefit would come from continually drying and rewetting the pitch but that would be difficult for any pitch without dedicated resources and time spent on its maintenance (or a different climate!).

4.2 Soil Shrinkage

The aim of this experiment was to develop a method to measure the effect of aeration on soil shrinkage as part of the soil's natural shrink-swell cycle. Ultimately the technique should be able to examine total soil shrinkage, the number of cracks that form, the speed of crack formation and the length and width of the cracks and how they are affected by aeration treatments.

The surfaces of thin cylinders of soil were photographed over time and the reduction in area analysed as a function of water content. Four soils were used of varying clay content from 0-32%. The cylinders of soil were monitored as they dried from a slurry to air-dry. The area of the soil surface was monitored over 72 h as a measure of the shrinkage of the soils and the results compared to the standard theory of soil shrinkage.

4.2.1 Introduction

4.2.1.1 Standard shrinkage theory

Soil shrinkage occurs to varying degrees in all soils, particularly those containing smectitic clays (Parker *et al.*, 1977; Boivin *et al.*, 2004). Despite notable differences between shrinking and swelling processes it is shrinkage that has been used to indicate soil shrink and swell capacity for engineering, agricultural and soil restoration applications (Grant, 2008).

Shrinkage behaviour of a poorly structured soil can be described as containing four phases: unitary, basic, residual, and structural (Groenevelt and Grant, 2004; Tariq and Durnford, 1993).

- Unitary shrinkage occurs above the saturation point of the soil. As the water is lost the soil shrinks directly proportionally to the water lost.
- Basic shrinkage occurs at a rate approximately equal to or slightly below that of unitary shrinkage. As the water content drops below saturation interparticle contact starts to restrict movement causing crack formation and allowing air into the soil, the water content at which this occurs is called the air-entry point (AEP) and marks the start of the basic phase.

- Residual shrinkage ends when the soil is oven-dry and occurs at a rate considerably below unitary shrinkage. Eventually shrinkage becomes increasingly restrained reaching the 'shrinkage limit.'
- Structured soils will exhibit an extra stage before basic shrinkage where there is little or no change in bulk volume. Structured soils contain stable macropores which will drain with little or no loss in bulk volume as water content decreases; once the pores are empty the basic stage begins.

4.2.1.2 Methods of measuring shrinkage

Determining the volume of a regularly shaped object is a simple matter, all one must do is simply measure the appropriate number of dimensions in order to accurately calculate the volume. Two methods of measuring soil shrinkage that rely on this in order to calculate the volume are linear shrinkage (McGarry, 2002) and Braudeau *et al.*, (1999). Braudeau *et al.* (1999) used a laser to measure the height and diameter of cylindrical soil cores whilst simultaneously measuring their mass to determine water content. Linear shrinkage involves the packing of reformed soil into a trough and measuring the length of the core as it shrinks. When measuring a highly expansive soil there is a danger that the soil will deform and crack reducing the accuracy of measurement and the requirement of regularly shaped soil samples restricts their use for field samples. Values of shrinkage from Linear Shrinkage have been shown to correlate well with other methods (Grant, 2008).

Determining the shape of an irregularly shaped object is far more challenging. Error in estimating the volume of irregularly objects by estimating the linear dimensions increases at the cube of the error (Grant, 2008). The use of Archimedes principle, measuring the displacement of a volume of water when the object is immersed, is one way to overcome this. In order to protect the soil from the water it must be surrounded by a water impermeable material. Tariq and Durnford (1993) encased their samples in a rubber membrane. Choice of the rubber membrane must be made carefully as it must be thin and flexible enough to adhere as closely as possible to the soil sample yet strong enough to prevent tears or breaks during the experiment. In between measurements air of chosen humidity was passed across the sample inside the membrane to dry the sample. Whilst the sample did not have to be removed from the membrane between measurements it did have to be removed from the water and is not automated. A similar method the Coefficient of Linear Extensibility (COLE) (McGarry, 2002; Grossman *et al.*, 1968) coats the soil in Sarin resin permeable to water vapour but impermeable to liquid water. A correction factor is needed to account for the volume of the resin (McGarry, 2002). The British Standard method also uses the Archimedes principle but uses mercury instead of water (British Standards Institution, 1990).

4.2.1.3 Time-lapse photography and image processing

An alternative approach to the methods described above for measuring soil shrinkage is time-lapse photography coupled with computer based image processing. This has two main benefits compared to manual methods.

The first of these is that image processing allows the easy measurement of the features of an irregularly shaped object in the plane of the picture. This is achieved by algorithms capable of distinguishing the soil from the cracks and calculating the reduction in soil area. Whilst the technique is not as informative as a fully three-dimensional examination like Tariq and Durnford (1993) as it measures only two-dimensions, it is simpler and, on balance, more precise. The accuracy of the experiment is limited by the size of the object relative to the size of the camera's sensor array and number of pixels; the smallest observable feature corresponds to one pixel.

The second benefit is the ease with which data collection can be fully automated. The initial set up of the camera and the data capture equipment does not need to be varied for each sample. As the process is automated once the sample is prepared it can be monitored at closer intervals and over longer periods of time with little additional effort on the part of the operator. This has the advantage of allowing the collection of data outside of working hours, at precise intervals, and without human error.

4.2.2 Method

The proposed method uses a single camera to monitor the two-dimensional shrinkage of a thin cylinder of soil.

Five soils were used in the experiment: clay (C), clay loam (OL), clay loam (BC), sandy clay loam (SCL), and sandy silt loam (SZL) characterised in Table 4.1.

4.2.2.1 Time-Lapse Photography

Each soil was mixed with water to a specific water content (Table 4.6) to form a slurry and then poured into a pre-weighed cylindrical vessel (internal diameter 96 mm, depth 9.2 mm). The excess soil was scraped from the top and the combined weight of the vessel and soil recorded. A camera placed facing directly over the surface of the soil recorded images at 15 minute intervals (Figure 4.9).

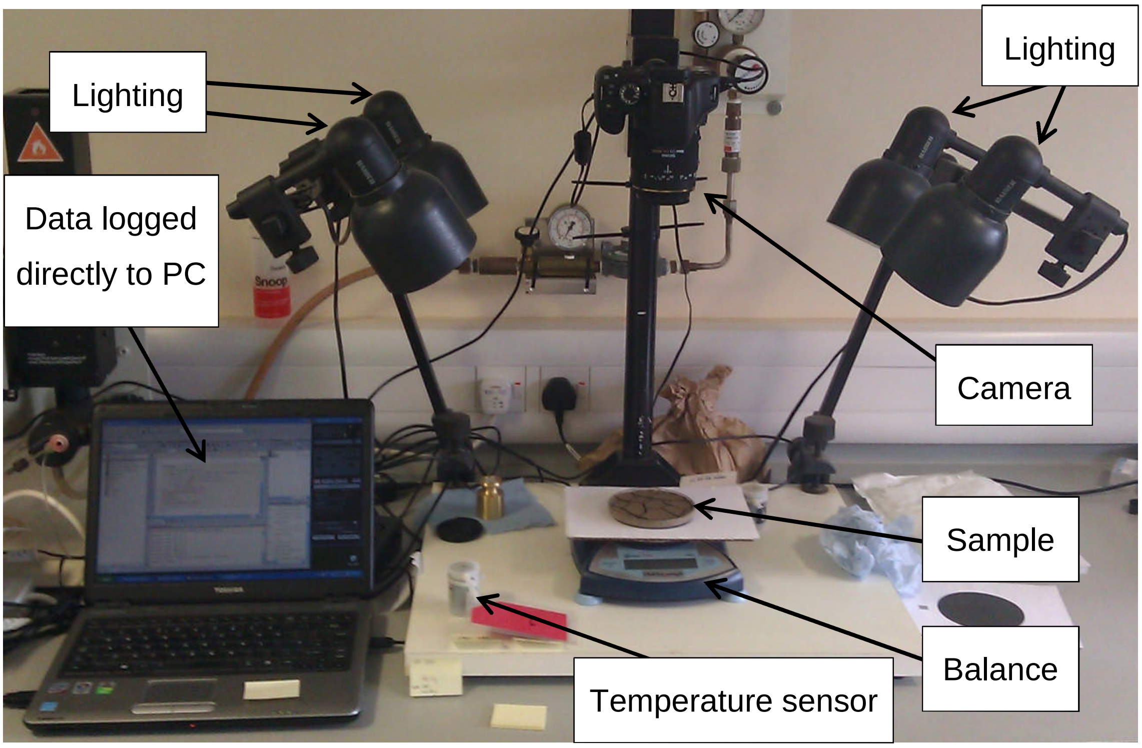


Figure 4.9 Captioned photograph of experimental setup.

The same photographic equipment was used as in Section 4.1.2.3 according to the settings listed in Table 4.5.

Table 4.5 Camera settings for time-lapse photography

Property	Details
F-stop	f/32
Exposure time	1/4 s
ISO speed	1600
Focal length	50 mm
Subject distance	400 mm

The combined weight of the vessel was recorded simultaneously so as to provide a record of water content for each picture using Matlab® (Mathworks, Natick, MA, USA) which was also used to process the images to provide a two-dimensional record of soil shrinkage with water content (Figure 4.10). The vessel was placed on a specially designed platform during photographing which contained a scale bar of known dimensions for size determination as well as providing a reference colour for any changes in lighting conditions. The photographing area was specially lit to maintain constant lighting conditions (Figure 4.9). The intensity of light and proximity of the bulbs to the soil required the use of low energy fluorescent lighting in place of traditional filament bulbs to reduce the ambient temperature around the soil sample created by the lighting. The temperature was recorded using two temperature sensors (Talk 2 Temperature Logger TK-4014, Tinytag, Chichester, UK) and was maintained at 22 ± 2 °C.

Table 4.6 Soil preparation parameters

Property	Soil				
	C	SCL	BC	SZL	OL
Water content (%m)	0.66	0.37	0.53	0.22	0.50
ρ_{solid} (g cm^{-3})	2.08	2.31	2.16	2.40	2.09

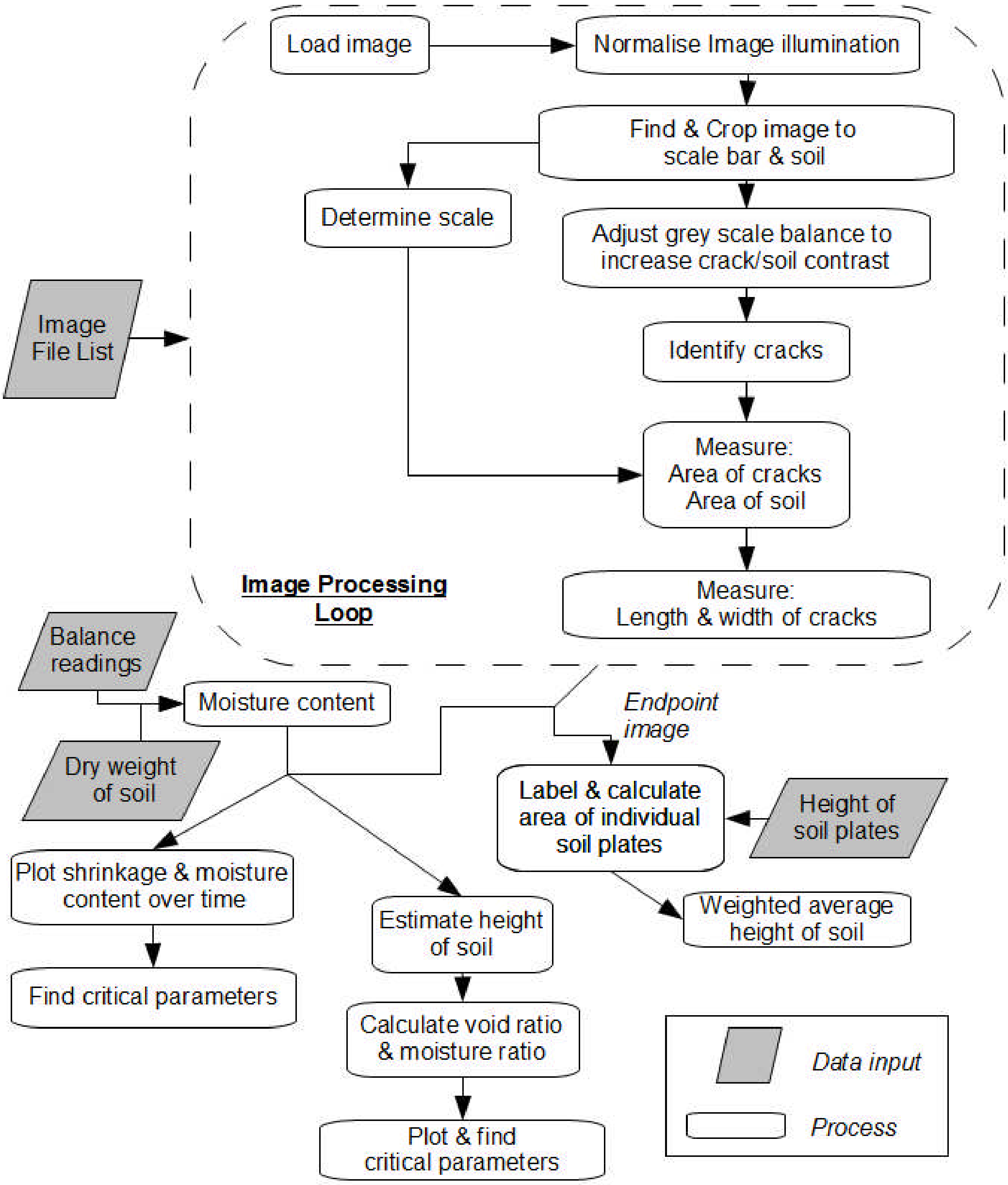


Figure 4.10. Programming flow chart

After 72 h for all soils shrinkage had ceased and the vessel was removed and weighed to ±0.01 g. The heights of the resulting soil plates were measured using a dial calliper to determine end-point vertical shrinkage to ±0.1 mm. Samples were then dried at 105 °C for 24 h and reweighed.

4.2.2.2 Water Release Curve

12 samples of each soil were prepared and saturated. Three samples of each saturated soil were placed on four sand tables set at 2.5×10^3, 5.0×10^3,

7.4×10^3 and 9.8×10^3 Pa. Upon reaching equilibrium each of set of three were then moved to the pressure cells providing three samples of each soil at each pressure: 1×10^5, 3×10^5, 9×10^5 and 15×10^5 Pa. The results were then averaged for each pressure to provide an overall water release curve for that soil.

4.2.2.3 Calculation of void ratio

Using the theory presented by Groenevelt and Grant (2004) a model of soil shrinkage was used for the estimation of the vertical height of soil using just the shrinkage data and the water content. The calculation assumes that prior to the soil cracking, the AEP, all shrinkage was directly proportional to the volume (and therefore the mass, assuming ρ_{water}= 1 g cm^{-3}) and occurred in the vertical dimension only. After the AEP it was assumed that all shrinkage was equidimensional (Grant, 2008).

Before the AEP vertical shrinkage was calculated using equation (4.1).

$$h_i = h_0 - \frac{m_0 - m_i}{\pi {r_0}^2} \qquad \textbf{(4.1)}$$

Where h_i is the height of the soil at time i, h_0 is the original height of the soil, m_0 is starting mass of dish and soil, m_i is mass of dish and soil at time i and r_0 is the inner radius of the dish.

After the AEP, equidimensional shrinkage was calculated by:

$$h_i = \frac{h_{AEP}}{r_0} \left(\frac{A_{soil}}{\pi}\right)^{\frac{1}{2}} \qquad \textbf{(4.2)}$$

Where, h_{AEP} is the height of soil at the AEP (as calculated by equation 1.1) and A_{soil} is the total area of soil. The calculation assumes that the reduction in height is directly proportional to the decrease in the radius of a circle that has the same area as the total area of soil.

The estimation of height allows for the calculation of the total soil volume, V_{total} and consequentially the void ratio, e, equation (4.3).

$$e = \frac{V_{voids}}{V_{solids}} = \frac{V_{total} - V_{solids}}{V_{solids}} \tag{4.3}$$

V_{voids} is volume of voids, V_{solids} is the volume of solid particles.

The moisture ratio, ϑ, is given by (V_{water} is the volume of water):

$$\vartheta = \frac{V_{water}}{V_{solids}} \tag{4.4}$$

4.2.2.4 Crack length, crack width and number of cracks

The cracks length, width and number require the images to be converted to binary black and white. The soil appears black and the cracks appear as white space. The number of cracks is counted by simply totalling the number of white areas completely enclosed by black areas. The length of cracks employs a thinning algorithm developed by Zhang and Suen (1984) which removes the white space of the cracks down to a single-pixel-wide line that delineates the centre of the crack. The centre lines are then measured for length; interconnected cracks are counted as a single crack. The width of the line is calculated by measuring the mean shortest distance between the centre line and the walls of the crack at each point along the length of the crack.

4.2.3 Results

The total shrinkage of each soil is closely correlated with clay content. The greater the clay content (Table 4.1) the greater the total amount of shrinkage (

Table 4.7) (Figure 4.11). Soil SZL showed no cracks and vertical shrinkage could not be measured as the soil structure was too weak to get intact samples for measurement.

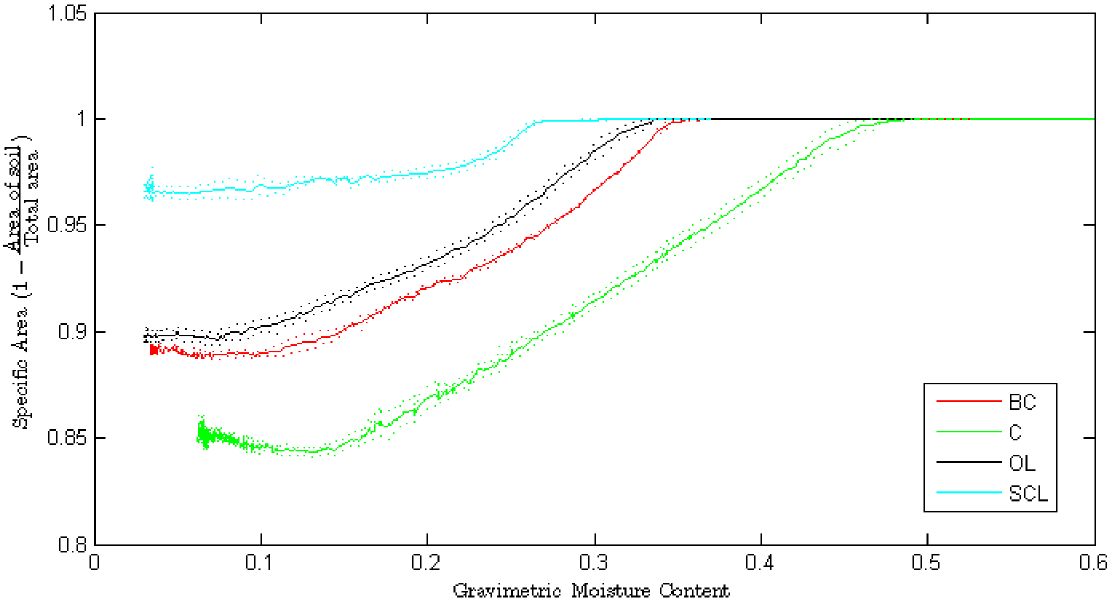


Figure 4.11 Specific soil area against gravimetric water content. Solid lines represent mean values, dashed lines show standard error of the mean.

The equipment is unable to observe shrinkage in the vertical dimension so it is unable to capture shrinkage till the soil starts to crack at the AEP. Due to the lack of a third dimension, instead of presenting the results in the standard soil shrinkage curve of specific volume against gravimetric water content, specific area is used instead.

$$Specific\ area = 1 - \frac{Area\ of\ soil}{Original\ area\ of\ soil} \qquad \textbf{(4.5)}$$

Soil C shows the clearest correlation with the predictions of the four phase model, with a long almost straight-line basic shrinkage phase, followed by rapid tailing off into residual shrinkage as water content decreases. Soils BC and OL follow a similar trend but displaced from each other. Both soils have a curved basic stage which then gradually leads into the residual phase. Soil SCL shows the smallest amount of shrinkage and also the shortest basic phase, moving very quickly into the residual stage as the water evaporates (Table 4.7).

Table 4.7 Shrinkage parameters

Property	Soil			
	BC	C	OL	SCL
Air-entry point				
Specific area, A_{AEP}	1	1	1	1
Water content, θ_{AEP}	0.38	0.49	0.34	0.32
Void ratio, e_{AEP},	0.58	0.89	0.48	0.59
Moisture ratio, ϑ_{AEP}	0.78	1.02	0.71	0.64
Residual phase start				
Specific area, A_{res}	0.89	0.84	0.89	0.98
Water content, θ_{res}	0.11	0.14	0.09	0.23
Void ratio, e_{res}	0.40	0.55	0.33	0.63
Moisture ratio, ϑ_{res}	0.24	0.30	0.19	0.53
Shrinkage limit				
Specific area, A_{lim}	0.89	0.85	0.90	0.97
Void ratio, e_{lim}	0.33	0.48	0.26	0.51
Other				
Basic phase length, $\theta_{AEP} - \theta_{res}$	0.27	0.35	0.25	0.09

Figure 4.12 shows estimated void ratio plotted against the moisture ratio. The largest amount of variation is in OL as indicated by the more dispersed error terms.

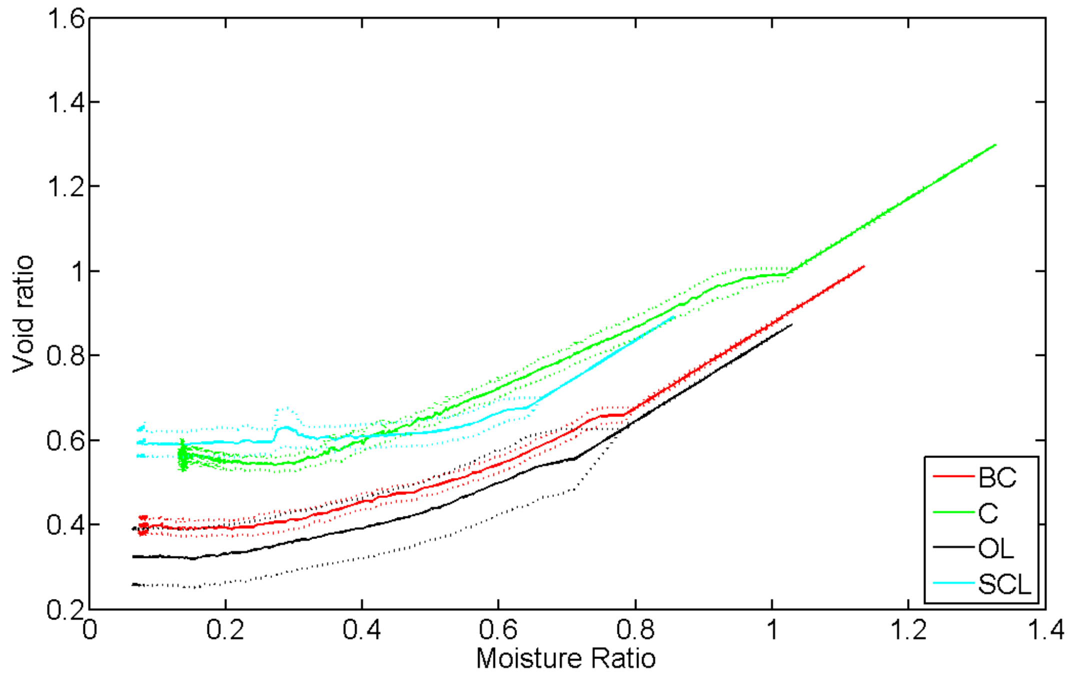


Figure 4.12 Void ratio versus moisture ratio. Solid lines represent mean values, dashed lines show standard error of the mean.

The same general trends observed in Figure 4.11 are present in Figure 4.12 although it becomes difficult to separate out the three phases observed in soil BC and OL as it seems the basic shrinkage phase is more a steady decline in shrinkage rate to the shrinkage limit rather than there being a clear separation where the rate begins to decline drastically marking the start of the residual phase.

4.2.3.1 Calculation of vertical shrinkage

The measured values of end-point soil height were different from the calculated values by varying amounts for each soil. Two methods of calculating the height were used, one utilises the radius of a circle with area equal to the area of soil, the second method utilises the reduction in area directly. The calculated values are always greater than the actual value causing the calculation of void ratio to underestimate the level of shrinkage (Table 4.8). The values calculated from the area of soil were not significantly different from the measured values ($p<0.05$). The differences calculated from the radius were significantly different at $p<0.05$.

Indicating that area is an improved basis for calculating the vertical shrinkage than the radius. The total effect on void ratio was small.

Table 4.8 Calculation of h and corresponding void ratios

Property	Soil			
	BC	C	OL	SCL
Measured h (mm)	6.76	6.38	6.83	7.292
Calculated (radius) h_r (mm)	7.15	7.32	7.23	8.01
Calculated (area) h_A(mm)	6.74	6.72	6.84	7.87
Void ratio from h, e_{actual}	0.32	0.36	0.25	0.45
Void ratio from h_r , e_r	0.33	0.48	0.26	0.51
Void ratio from h_A, e_A	0.32	.045	.026	0.56

4.2.3.2 Crack length, crack width and number of cracks

The photographs corresponding to the AEP/start of basic shrinkage, end of basic shrinkage/start of residual shrinkage, and the shrinkage limit were assessed for the number of cracks formed, the width of the cracks and the length of the cracks.

The number of cracks shows the greatest variation with time and soil type (Figure 4.13 and Table 4.9).

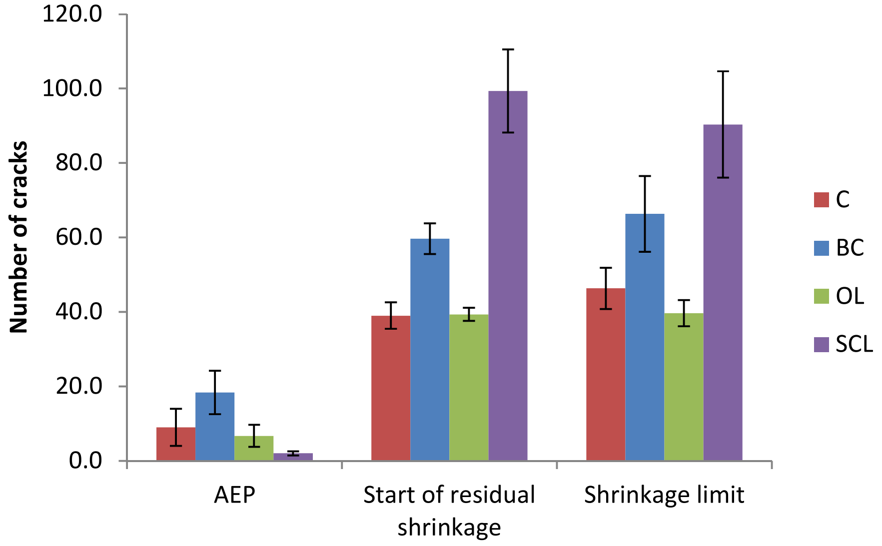


Figure 4.13 Mean number of cracks for each soil over the three replicates at each of the time points. Verticals bars denote standard error.

Table 4.9 Homogenous groups at p<0.05 in Figure 4.13 for the mean number of cracks in each soil at each time point.

Grouping	Time	C	BC	OL	SCL
Within soil	AEP	a	a	a	a
	Start of residual shrinkage	b	b	b	b
	Shrinkage limit	b	b	b	b
Within time	AEP	α	α	α	α
	Start of residual shrinkage	β	α	β	χ
	Shrinkage limit	αβ	α	β	χ

Soil SCL forms the greatest number of cracks, followed by Soil BC. Soil OL and Soil C form the least number of cracks and are generally not significantly different from each other.

Over time it appears that most cracks are formed during the basic shrinkage phase as for each soil there was no significant difference between the number of cracks at the start of the residual phase and the shrinkage limit.

The width of cracks formed generally showed little variation over both time and soil type (Figure 4.14 and Table 4.10).

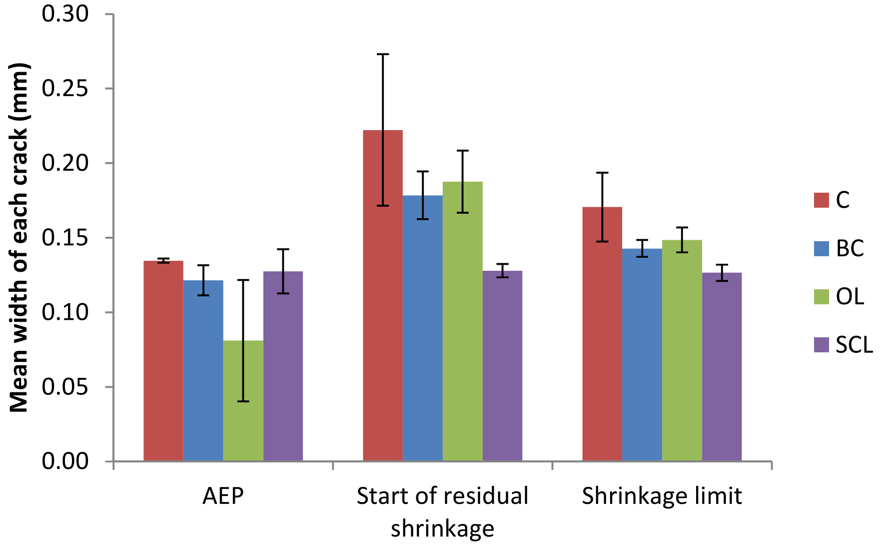


Figure 4.14 Mean width of cracks formed for each soil over the three replicates at each of the time points. Verticals bars denote standard error.

Table 4.10 Homogenous groups at p<0.05 in Figure 4.14 for the mean width of cracks in each soil at each time point.

Grouping	Time	C	BC	OL	SCL
Within soil	AEP	a	a	a	a
	Start of residual shrinkage	b	a	b	a
	Shrinkage limit	ab	a	b	a
Within time	AEP	α	α	α	α
	Start of residual shrinkage	α	αβ	αβ	β
	Shrinkage limit	α	α	α	α

Only Soil C and Soil OL showed any variations over time with a smaller width at the AEP point than in the latter stages. Within each shrinkage point there were only differences between soils at the start of residual shrinkage between Soil C and Soil SCL.

The mean length of individual cracks in each soil, like crack width, showed limited variation between times and soils (Figure 4.15 and Table 4.11).

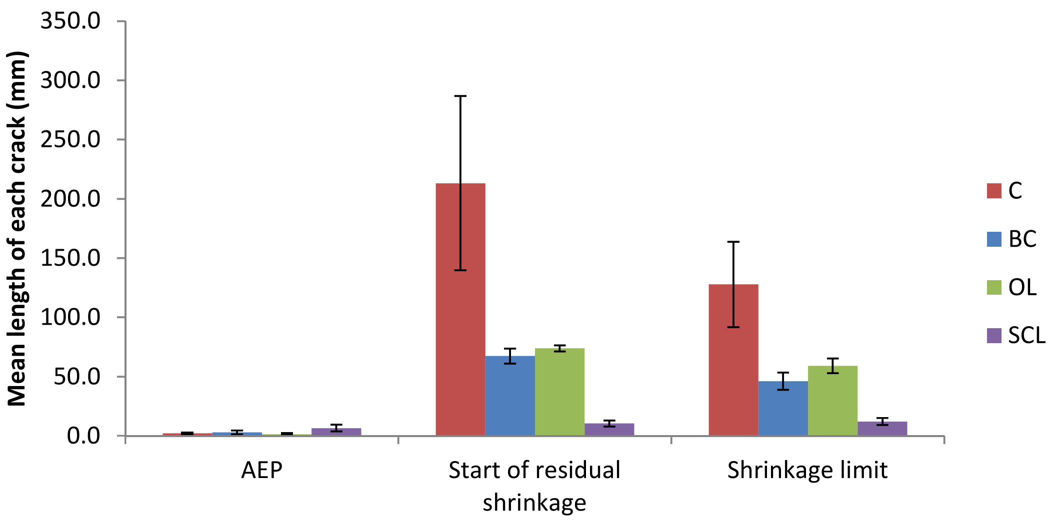


Figure 4.15 Mean length of cracks formed for each soil over the three replicates at each of the time points. Verticals bars denote standard error.

Table 4.11 Homogenous groups at p<0.05 in Figure 4.15 for the mean length of cracks in each soil at each time point.

Grouping	Time	C	BC	OL	SCL
Within soil	AEP	a	a	a	a
	Start of residual shrinkage	b	a	b	a
	Shrinkage limit	c	a	ab	a
Within time	AEP	α	α	α	α
	Start of residual shrinkage	β	α	α	α
	Shrinkage limit	β	α	$\alpha\beta$	α

Soil C and Soil OL showed variations with time, both showed increased crack length from AEP to start of residual shrinkage. Soil BC and Soil SCL showed no significant variations with time in crack length. Soil C showed a greater average crack length than the remaining soils. The way the algorithm works will count any connected cracks as one crack so a highly connected crack network will have one very large crack and several much smaller cracks (Figure 4.16). As such the mean length of crack will be highly affected by how many smaller cracks are formed and will not reflect the true length or distribution of cracks. Consequently the total length of cracks will be considered instead.

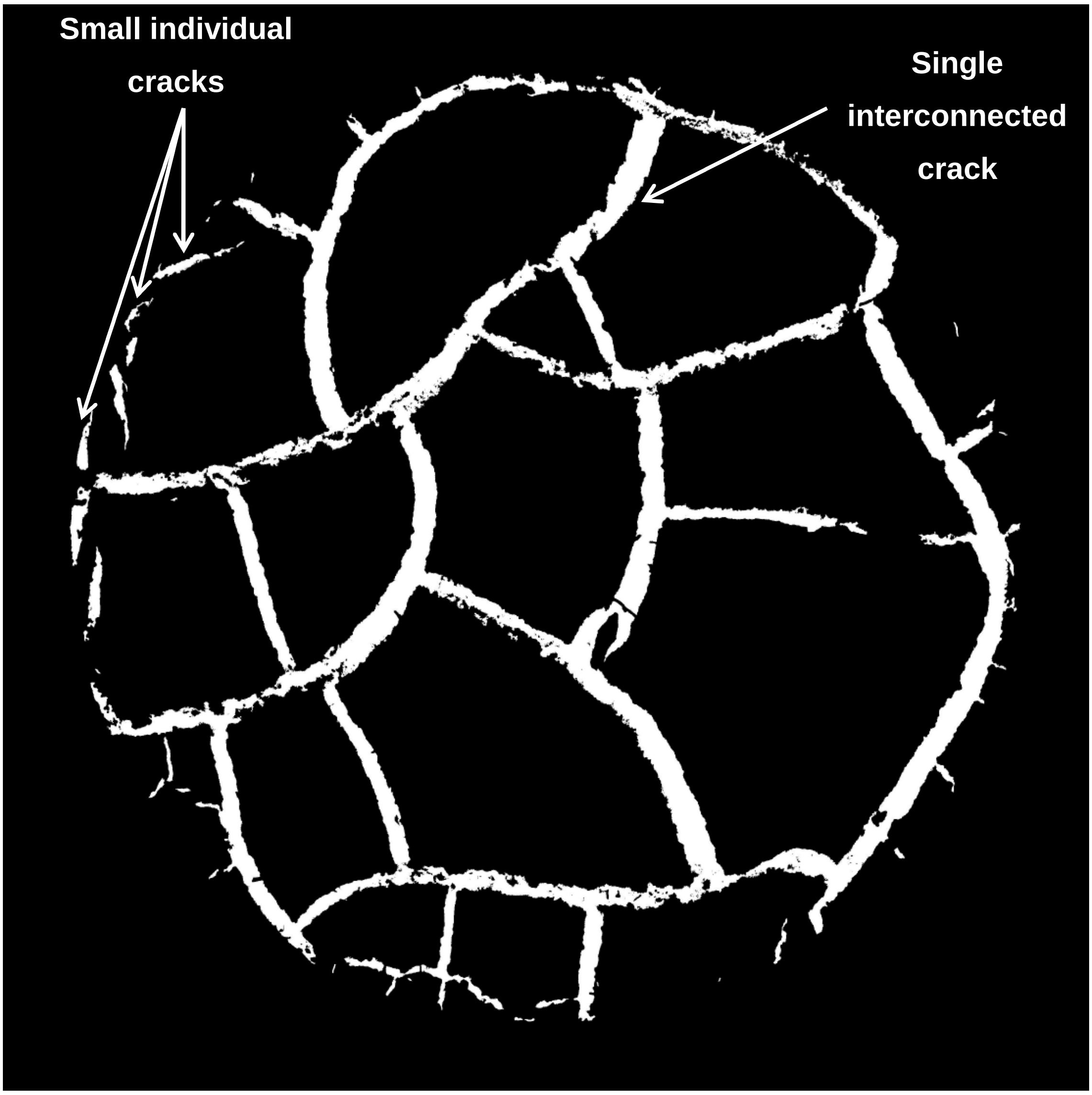


Figure 4.16 Example binary image from Soil C demonstrating a single interconnected crack and several small cracks that have formed.

Figure 4.17 shows the total length of cracks formed during the shrinkage process at the three selected points. As expected there is considerably more cracks at the start of residual shrinkage and very few at the AEP as this is the point when the cracks are only just beginning to form. There is no significant difference in total crack length between the start of residual shrinkage and the shrinkage limit in any of the soils. Soil C forms the most extensive length of cracks but also the greatest variability and so is not significantly different from Soil O and Soil BC. Soil SCL forms significantly less cracks than the other soils ($p<0.05$).

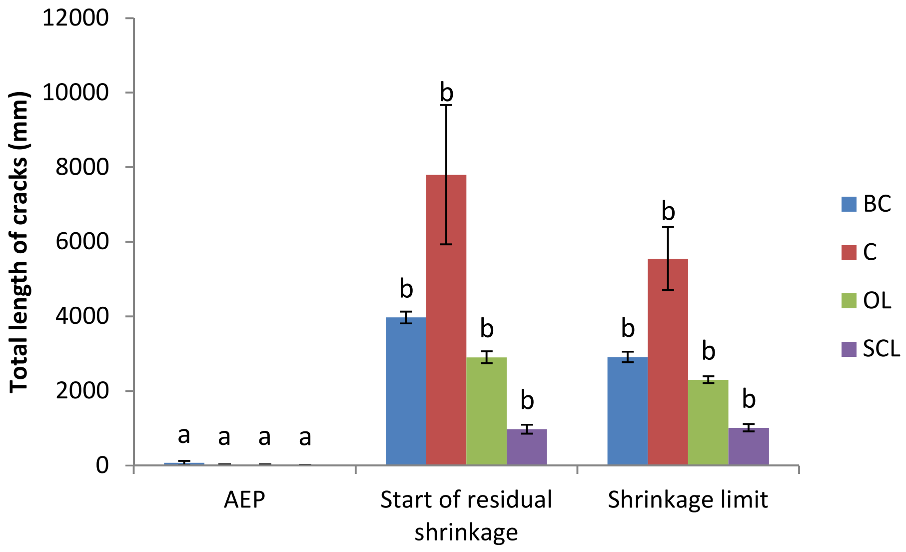


Figure 4.17 Total length of cracks at three stages in the shrinkage process for each soil as a mean of each of the three reps. Vertical bars denote standard error. Letters indicate homogenous groups within each soil type at p<0.05.

4.2.4 Discussion

Stirk (1954) found that the lower the clay content the higher the moisture potential at which the shrinkage moves from basic to residual. This holds true for all the soils tested. The (shrink-swell) inactive sand and silt particles form a rigid non-deformable matrix that inhibits macroscopic shrinkage. The greater the content of sand and silt, the greater the effect until macroscopic shrinkage is inhibited altogether, as in the case of Soil SZL. Soil SCL showed the smallest range in water content between entering residual shrinkage and AEP.

This experiment demonstrates the effective monitoring of shrinkage in a range of soils using time-lapse photography and image processing. All the soils observed showed typical shrinkage patterns in line with the accepted theory. All soils showed three stages of shrinkage expected in an unsaturated soil: unitary to the AEP, basic to the residual inflection, and residual shrinkage to the shrinkage limit. The difference in water content between the AEP and residual inflection point is linked to clay content (Stirk, 1954).

4.2.4.1 Calculations of vertical shrinkage

The method is two-dimensional as the third dimension, height, was not recorded during the experiment. In order to convert the method from two-dimensions to pseudo three-dimensions the height was estimated from the water content data and lateral shrinkage based on the multi-stage model (Groenevelt and Grant, 2004; Tariq and Durnford, 1993). Agreement between the estimated end-point height and the measured height was good when calculated from the area but poor when calculated from the radius. In every case the calculated value underestimated the extent of vertical shrinkage (i.e. the soil was thinner than calculated) leading to an overestimation of the void ratio by giving a larger total volume. The extent of the overestimation was not consistent between soils, Soils C and SCL, the greatest and least shrinking soils respectively, showed the highest discrepancy; soils BC and OL showed the same level of discrepancy. The model used in calculating h assumes that all shrinkage before the soil cracks occurs in the vertical dimension only – given that the soil would crack if there was lateral shrinkage this assumptions appears valid. After the AEP it is assumed that vertical shrinkage is proportional to lateral shrinkage. It is possible that the method of assessing lateral shrinkage underestimates the extent. The soil as it faces the camera is in a circle. The method calculates the total area of soil (cracks are not counted as soil) and calculates the radius of a circle of the same area, the rate of reduction in the radius is then used to calculate vertical shrinkage. Doing the calculation in this way gives the smallest reduction in height for each unit of area the soil shrinks. An alternative is to use the reduction in the area of soil relative to the starting area of soil as a basis for the reduction in height. Table 4.8 summarises the results from the two different methods of calculating h. The values calculated from the area of soil were not significantly different from the measured values ($p<0.05$). The differences calculated from the radius were significantly different at $p<0.05$. Indicating that area is an improved basis for calculating the vertical shrinkage than the radius. The total effect on the void ratio was small and when compared the values of void ratio were not significantly different between the two height calculations.

4.2.4.2 Crack length, crack width and number of cracks

The cracking properties of the soils showed little differences between the soils tested except for Soil SCL. Two possibilities present as to the nature of the soil particles size distributions that may affect the cracking properties based on this evidence. The first relates to a possible critical level of clay content that ensures similar cracking patterns in the soil. This is based upon the greater clay content of Soils C, BC and OL compared to Soil SCL but also the markedly different makeup of the remaining components of the Soil in BC, OL and C, Soil BC has a greater sand content and lower silt content than Soil OL yet show similar properties in cracking patterns indicating that in this case the clay content is the dominant factor. The alternative theory is the much greater sand content in Soil SCL is responsible for the change in cracking patterns but as there is no difference between Soil BC and Soil OL this seems unlikely.

The general trend is, with increasing clay content, the total length of cracks increases and the number of cracks decreases. Soil SCL forms a higher number of small isolated cracks whereas the remaining soils form a smaller number of highly interconnected cracks. Both the number of cracks and the total length of cracks follows the same trend over time, indicating that by the start of residual shrinkage all the cracks have already formed and will widen rather than new cracks form. The width of the cracks did not seem to significantly increase but this measurement showed the greatest level of variation and so the increase could have been missed.

Baker *et al.* (1998b) examined cracking patterns in several soils and concluded that the patterns were a result of complex interactions between clay content, clay mineralogy and organic matter content. The results tend to agree with this rather broad statement, concluding that increased clay content leads to a greater amount of cracking due to the increased extent of shrinkage the clay component creates.

4.2.4.3 Limitations & Future Work

Ideally the method should be calibrated against a known standard method of measuring shrinkage, such as linear shrinkage. As discussed the lack of soil height information before the end-point is a crucial problem when monitoring what is a three-dimensional process. Whilst a comparison using fewer dimensions is possible and has been done for comparing linear shrinkage with COLE (McGarry, 2002) the ideal solution would be to monitor all three dimensions. The most obvious option is to use a laser to measure the height as in Braudeau *et al.* (1999).

Further work is needed to measure the crack width, length and speed of formation. Whilst it is easy to develop pictures of the soil crack network (Figure 4.18) examination of the crack network is a non-trivial matter and highly computationally heavy. Algorithms exist that can count the length and width of the cracks but logically defining a single crack is difficult; as the cracking process continues eventually there is generally just one highly connected (with itself) crack and a few small individual cracks. A more informative view would have been gained had the total crack length over time been determined and examined in relation to the extent of shrinkage and is suggested for future work.

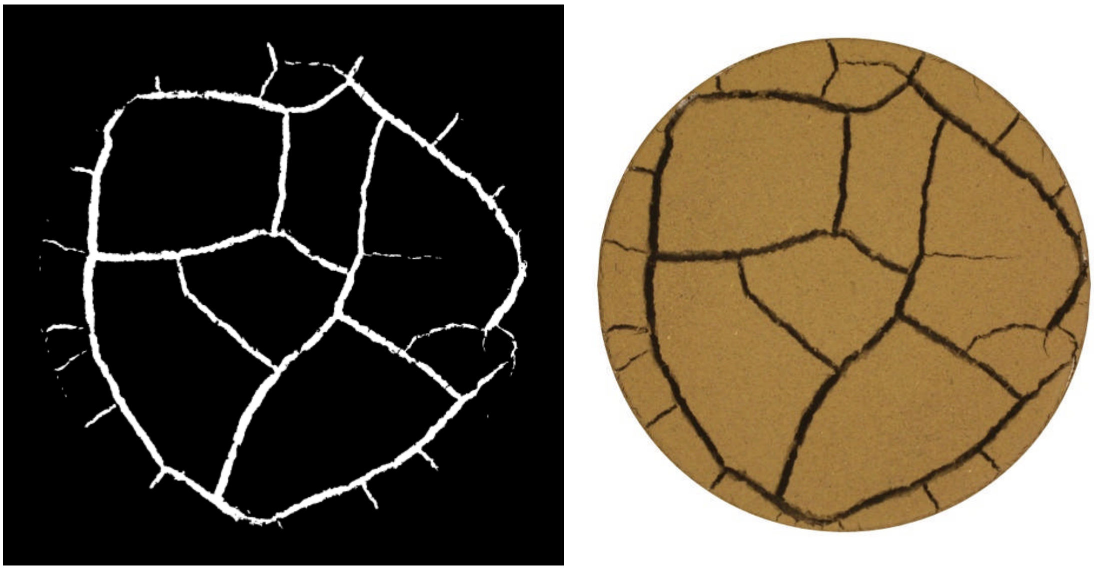


Figure 4.18 (Left) Binary image of the soil, white space are cracks; (Right) Corresponding image of the soil

The output from the crack width and length examination was not calibrated against a standard method and is a suggestion for a future small research project. Optimisation of the algorithms to decrease the time taken to examine each photograph (currently taking several hours per picture) would greatly increase the power of this technique as it would allow the analysis of more points in time. The drying conditions for each soil and for each repetitions were maintained at a constant level and hence the experiment does not take into account the rate of drying in the cracking profiles and varying it has been highlighted as a potential factor in cracking patterns (Baker *et al.*, 1998a).

4.2.5 Conclusions & relevance to cricket

The method as a way of monitoring shrinkage appears to function extremely well. It is unfortunate that it was not possible to develop the necessary programming capability to properly accomplish the aims of the experiment; however an excellent foundation has been laid for the expansion of the method to achieve this with some insights into the effect of different clay, sand and silt components on the cracking patterns of soils. Importantly the range of clay contents examined between Soil BC, OL and C made no difference to the cracking patterns observed and the clay component appeared to dominate over the effects of the sand and silt. As such it would appear that having a higher sand content, providing the clay content was above the critical level, will not affect cracking patterns. Having a higher sand content increases the average pore size and leads to better drainage and increased evapotranspiration (Section 7) so the soil has a tendency to have a lower moisture content and greater air-filled porosity resulting in increased gas exchange with the atmosphere. Thus a greater sand content pitch in terms of oxygenation is easier to manage and may reduce the reliance on aeration as a means to achieve this.

Reducing the reliance on mechanical treatments has several benefits. Firstly, the application of the treatments can be damaging to the soil and the plant as the machines are often heavy and applied in late autumn when the ground is wet. Secondly it reduces the resources cost of maintaining the pitch, not only in requiring less fuel for the machine but also in time spent applying the treatment. Clearly a pitch that can look after itself without a significant reduction in performance capability is an advantage.

The experiment detailed here provides little scope for stating outright that a greater sand content is better for reducing the difficulty in managing a cricket pitch as it is examining the potential effects from the standpoint of aeration only. The experiment does show that considerable benefits could be achieved by closer consideration of the soil types used in profile construction and it is suggested that a future research project could examine the potential for performance gains and maintenance reduction from manipulating the soil constituents. Given that most cricket loams are generated from blended sources creating a more tightly-specified, engineered soil would not be very difficult.

4.3 Shrinkage and Swelling Processes

Both the shrinkage and the swelling characteristics of each soil were dependent on clay content. Those that swelled the most and those that shrank the most both had the greatest quantity of clays.

The similarity of the shrinkage curves and the cracking dynamics amongst the soils indicates the dominance of the clay content in this process compared to sand and silt. The shrinkage process appears to follow a much simpler dependence on clay content but shows a step dependency as the range of clay content in Soil O (30.1%) to Soil C (47.2%) appeared to have little effect on cracking patterns, whereas the lower clay content of Soil SCL (19.9%) was. The swelling process had an additional dependence on the pore size distribution occurring via two distinct methods compared to the single shrinkage process. The shrinkage values are generally lower than the swelling values as there is not the addition of air entrapment effects in shrinkage.

When combined with the air entrapment process from swelling which is aided by having a heterogeneous pore size distribution the addition of a greater sand content to the soil has increased benefits in terms of increasing the extent and rate of swelling. Thus a higher sand content not only improves the natural aeration status of the soil but also improves the potential for recovery from compaction via natural processes.

5 Laboratory Scale Examination of Diffusion in Soil

Gas diffusion through high density soil is slow due to low porosity, small pores and high tortuosity. There is very little research on the effect of aeration on gas diffusion into the soil. What work has been done is based on sandy soils.

The rate of oxygen diffusion into the soil profile from an initial oxygen-free state was measured at four depths. Two water contents were examined, 25%m and 23%m. The greater soil water content caused a dramatic reduction in the rate of oxygen diffusion into the soil. Solid tine aeration when compared to a no aeration treatment caused a significant increase in oxygen concentrations at depths below 125 mm.

5.1 Introduction

As described in Section 1 some of the principal aims of aerating are to reduce the effects of soil compaction to achieve:

- Improved rooting density and depth
- Improved gas exchange between soil and atmosphere

This experiment aims to examine the effect of solid tine aeration on soil gas exchange. The solid tine was chosen as it is the principal method of aeration on UK cricket pitches (Section 3).

Measuring the diffusion characteristics of soil is a difficult and complex problem. The heterogeneous nature of soil and interactions between various factors all impact on soil diffusion (Section 2)

It seems a logical extension that creating large hole in the soil will increase the rate of oxygen diffusion in the soil. Large artificial macropores coming straight from the atmosphere into the soil should allow for reduced tortuosity and increased connectivity of the pore network facilitating the easier movement of gases into and out of the soil. With soil this is not necessarily the case. As no soil is removed during solid tining significant compaction can occur around the tine hole, particularly at the base (Murphy *et al.*, 1993). Petrovic (1979) used CT scanning to examine the compaction around holes created by hollow tines in sand and found that the compaction along the walls dissipated quickly as the soil sloughed off into the hole but compaction at the base persisted for extended periods of time (>90 days). In a clay soil, particularly when wet, there is an added factor of smearing along the walls of the tine hole effectively sealing the hole. The more cohesive clay is less likely to slough and collapse like a sand. Holes with smeared smooth walls encapsulated by a layer of compacted soil do not necessarily then make soil more likely to be permeable to oxygen diffusion.

No previous research has been found for the effect of solid tines on oxygen concentration in the soil. Previous research on the effect of hollow tines in sands found variable results, one study found increased oxygen diffusion rates and another no effect (Murphy *et al.*, 1993).

5.1.1 Diffusion in free atmosphere

Diffusion is the net movement of molecules from an area of high concentration to an area of low concentration. Diffusion is a result of the random motion of individual molecules creating a net flow from the high concentration area to the low concentration area. Individually the probability of a molecule ‘random walking’ from the higher concentrated area to the lower concentration area is the same as one ‘random walking’ out of the low concentration area to the high concentration area; it is the relative numbers of molecules in each area that creates a net flow from high concentration to low concentration area as the number of molecules in the high concentration area is greater. Thus while the same probability exists for each molecule to move from one area to another there are a greater number of molecules in the high concentrated area that can ‘random walk’ to the low concentrated area. While the random movements of individual molecules make up the mechanism of the process, on the macroscale it is seen as a smooth flow of material from the high concentration to the low concentration. Fick’s first law (Equation (5.1)) describes the behaviour of the macroscale smooth flow (assuming steady state conditions, i.e. the system is not altered over time) linking the concentration gradient to the diffusive flux (the amount of diffusing substance passing through a specific area per unit time).

$$J = -D\frac{\partial C}{\partial x} \tag{5.1}$$

Where J is the diffusive flux (mol m^{-2} s^{-1}), D is the diffusion coefficient (m^2 s^{-1}), C is the concentration (mol m^{-3}) and x is the distance from source (m). The unit of concentration does not have to be moles, but it must be expressed per unit volume (and applied consistently).

Fick's first law describes the movement of the diffusing gas through a reference gas (Crank, 1975). The equation defines mathematically the rate of transfer of the diffusing gas through a unit area. The direction of transfer follows the path of, and is proportional to, the negative concentration gradient normal to the surface through which diffusion is occurring.

5.1.2 Fick's 2nd law describes non-steady state diffusion

Fick's first law can be used to derive Fick's second law using the conservation of mass to attain the familiar diffusion equation (Crank, 1975):

$$\frac{\partial C}{\partial t} = D\nabla^2 C \tag{5.2}$$

Where, C is concentration of the gas, t is time. If diffusion is occurring in one-dimension only this can be simplified to:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{5.3}$$

Where, x is distance from source. Equation (5.3) describes the change in concentration over time and so can be used to calculate the diffusion coefficient in non-steady state conditions. This partial differential equation is more difficult to solve than Equation (5.1), however, for certain boundary conditions exact solutions can be found (Stępniewski and Gliński, 1985; Crank, 1975). Far simpler to implement is a finite difference solution that uses Taylor series to approximate the solution to Equation (5.3) over discrete time and distance steps.

5.1.2.1 Crank-Nicolson: finite-differences

The Crank-Nicolson method uses the central difference at time $t_{n+\frac{1}{2}}$ for the time derivative and the second order central difference about coordinate x_j (Appendix B). Equation (5.3) can be approximated to:

$$\frac{C_j^{n+1} - C_j^n}{\Delta t} = \frac{D}{2}\left\{\frac{\left(C_{j+1}^{n+1} - 2C_j^{n+1} + C_{j-1}^{n+1}\right)}{(\Delta x)^2} + \frac{\left(C_{j+1}^{n} - 2C_j^{n} + C_{j-1}^{n}\right)}{(\Delta x)^2}\right\} \quad \textbf{(5.4)}$$

To solve this equation for D, six measurements of concentration are required (Figure 5.1).

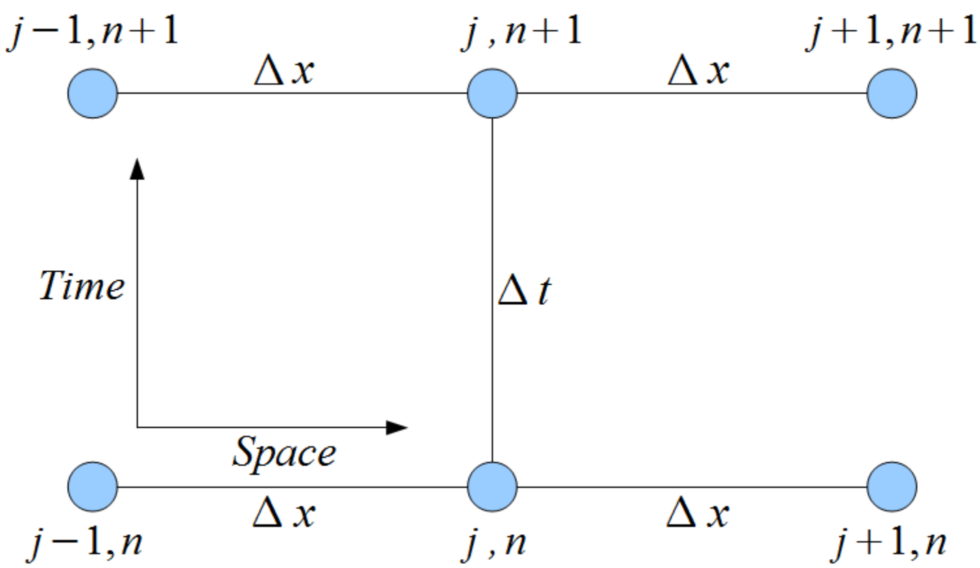


Figure 5.1 Stencil illustration of finite difference scheme

Plotting the approximation of the time derivative:

$$\frac{C_j^{n+1} - C_j^n}{\Delta t} \quad \textbf{(5.5)}$$

Against the approximation of the space derivative:

$$\frac{\left(C_{j+1}^{n+1} - 2C_j^{n+1} + C_{j-1}^{n+1}\right)}{(\Delta x)^2} + \frac{\left(C_{j+1}^{n} - 2C_j^{n} + C_{j-1}^{n}\right)}{(\Delta x)^2} \quad \textbf{(5.6)}$$

Will yield a graph of slope $D/2$.

5.1.3 Diffusion in porous media

Equations (5.1) and (5.3) are only representative of diffusion in open spaces with no solid objects acting as barriers to the free movement of the gas molecules. Clearly this is inadequate to explain the diffusion of gases in the soil. The soil particles reduce the cross sectional area available for diffusion as well as increasing the pathway for gas exchange (Figure 5.2).

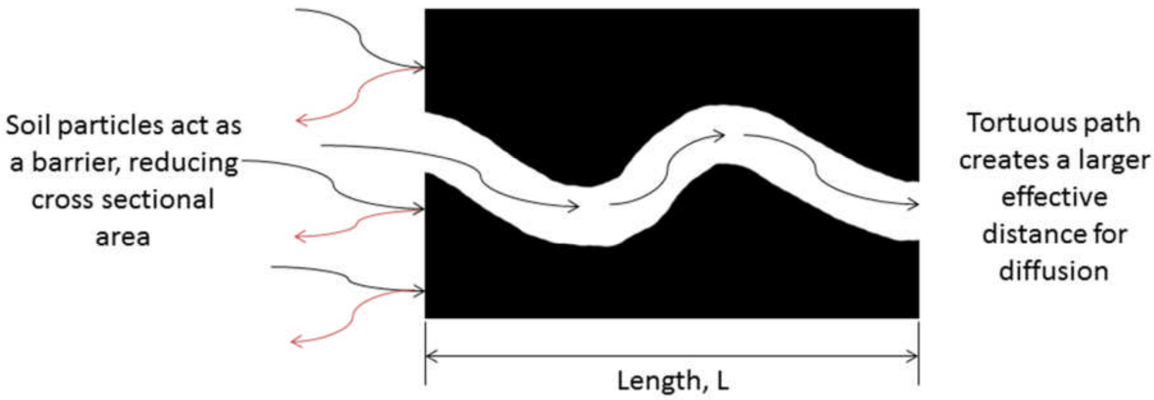


Figure 5.2 Illustrated effect of soil particles (black) reducing the available space (white) and cross sectional area for diffusion as well as increasing the length of the pathway over which diffusion occurs.

Attempts to account for this are based around the air-filled porosity of the soil and an impedance factor generally linked to water content which reduces the diffusion coefficient in an attempt to relate the diffusion coefficient in air, D_0, with experimentally derived values of the diffusion coefficient in soil, D_s (Moldrup *et al.*, 2001; Currie, 1970; Penman, 1940; Millington and Quirk, 1961; Moldrup *et al.*, 2000) D_s and D_0 are both dependent on the type of gas, the temperature, and pressure. D_s is also dependent on the air-filled porosity, the tortuosity and the connectivity of pores. D_s/D_0 is the relative diffusion coefficient, a dimensionless quantity with the gas type, temperature and pressure dependency removed leaving only the air-filled porosity, connectivity and tortuosity of the pore network as factors. ${D_s}/{D_0}$ characterises the capability of the soil for gas exchange and hence was the subject of much research to attempt to relate it to more easily measured or calculated parameters of the soil. Currie (1984) concluded that no single relationship between D_s, D_0 and air-filled porosity found would fit all the results in an aggregated system. This is because the pore network is effected very differently in a non-aggregated system (upon which the other models were based) when water is added to the system as the aggregates can fill with water without compromising the pore network between them (remembering that a water filled pore is effectively a barrier to gas diffusion).

By comparing the relative diffusion coefficient of unaerated soil to aerated soil this should provide a quantifiable basis for analysing the effect of aeration on the soils ability to transport and exchange gases with the free atmosphere.

5.1.4 Diffusion coefficient in a changing mixture of gases

The diffusion coefficient for oxygen moving through the soil air may be slightly different from that in the atmosphere if the carbon dioxide concentrations become elevated. To calculate the oxygen diffusion coefficient under changing carbon dioxide concentration (Fairbanks and Wilke, 1950):

$$D_{1-mix} = \frac{1}{\left(\frac{y_2}{D_{1-2}}\right)+\left(\frac{y_3}{D_{1-3}}\right)+\cdots+\left(\frac{y_n}{D_{1-n}}\right)} \qquad \textbf{(5.7)}$$

Where D_{1-mix} is the diffusion coefficient of oxygen in the mixture, D_{1-n} is the diffusion coefficient of oxygen in constituent n and y_n is the mole fraction of constituent n calculated by:

$$y_n = \frac{y_n}{y_1 + y_2 + \cdots + y_n} \qquad \textbf{(5.8)}$$

The variability of the diffusion coefficient is small over the range of gas mixes (4.6%) (Table 5.1). It is unlikely that the carbon dioxide concentrations will rise above 10%v and given the variability of the soil this source of error, whilst acknowledged, will not be considered further.

Table 5.1 Oxygen diffusion coefficient calculated for different gas mixes using Equation (5.7) and (5.8).

Oxygen concentration (%v)	Nitrogen concentration (%v)	Carbon dioxide concentration (%v)	D_{O_2-mix} ($cm^2\ s^{-1}$)
21	79	0	0.219
19	79	2	0.216
16	79	5	0.214
11	79	10	0.209

5.2 Method

The basic experimental unit consists of a plastic 410 mm deep bucket, internal diameter of 300 mm at base and 345 mm at top (Figure 5.3). Soil is packed into the tub in the following order: 50 mm of 5mm diameter gravel beneath 315 mm of soil packed at 1.55 ± 0.05 g cm^{-3} in three layers of 105 mm using a 4.5 kg standard proctor test hammer. Consistency of packing was achieved by using a regular pattern of blows across the surface to achieve a level surface of the specified height, the weight of soil in each layer was calculated to compensate the increased volume of the tapering sides of the bucket as the height of soil increased. The weight of the bungs, gravel, pipe and bucket were recorded along with the water content and packed weight of soil for later calculation of soil water content from total mass. 350 mm lengths of pipe were placed through the width of the bucket piercing opposing walls of the container at four different depths (Figure 5.3).

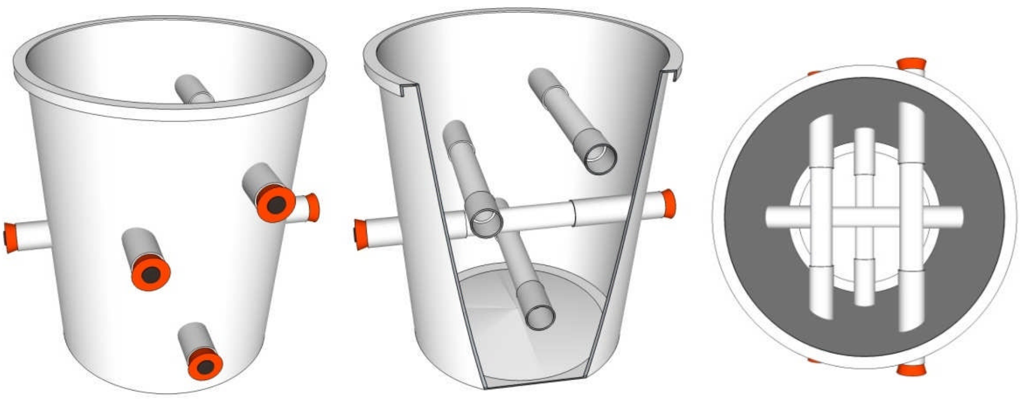


Figure 5.3 Empty experimental unit (left), sectioned view of unit (middle) and plan view of unit (right)

The 350 mm of tubing consists of 150 mm of LDPE porous tubing (through which gases can diffuse but not liquid water) and two 100 mm lengths of impermeable PVC tubing. The PVC tubing was sealed with predrilled rubber bungs in turn sealed with septa for sample collection (Figure 5.4).

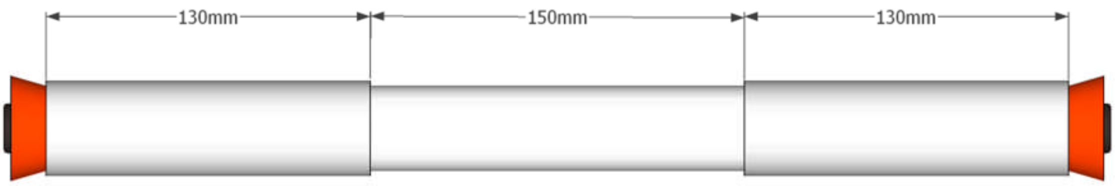


Figure 5.4 A dimensioned diagram of a complete section of tubing showing sealing bung, impermeable tubing and centrally located permeable tube.

The 150 mm of porous tubing is located at the midpoint between the two walls of the container. The areas where the tubing penetrates the wall of the container were sealed with a hard setting epoxy resin (Huntsman Advanced Materials, Cambridge, UK). The container was fitted with a valve at the base, the inlet valve, and a second valve fitted at the top through the lid of the container, the outlet valve. For the duration of the experiments each Unit was placed on a balance (Defender 3000, Ohaus Switzerland) and its weight (± 20 g) recorded at five minute intervals using Matlab (Mathsoft, Natick, Massachusetts, USA). Allowing calculation of the water content to ± 0.5 %m.

Water content was maintained at constant level by misting the soil surface twice daily.

Aeration was carried out using a solid metal tine driven into the soil to a depth of 75 mm. A template was used to ensure exact replication of the aeration pattern each time in a square pattern with 50 mm spacing. The pattern of tine holes was arranged so that the tube at depth 55 mm fell at the midpoint of two rows of tines (Figure 5.5).

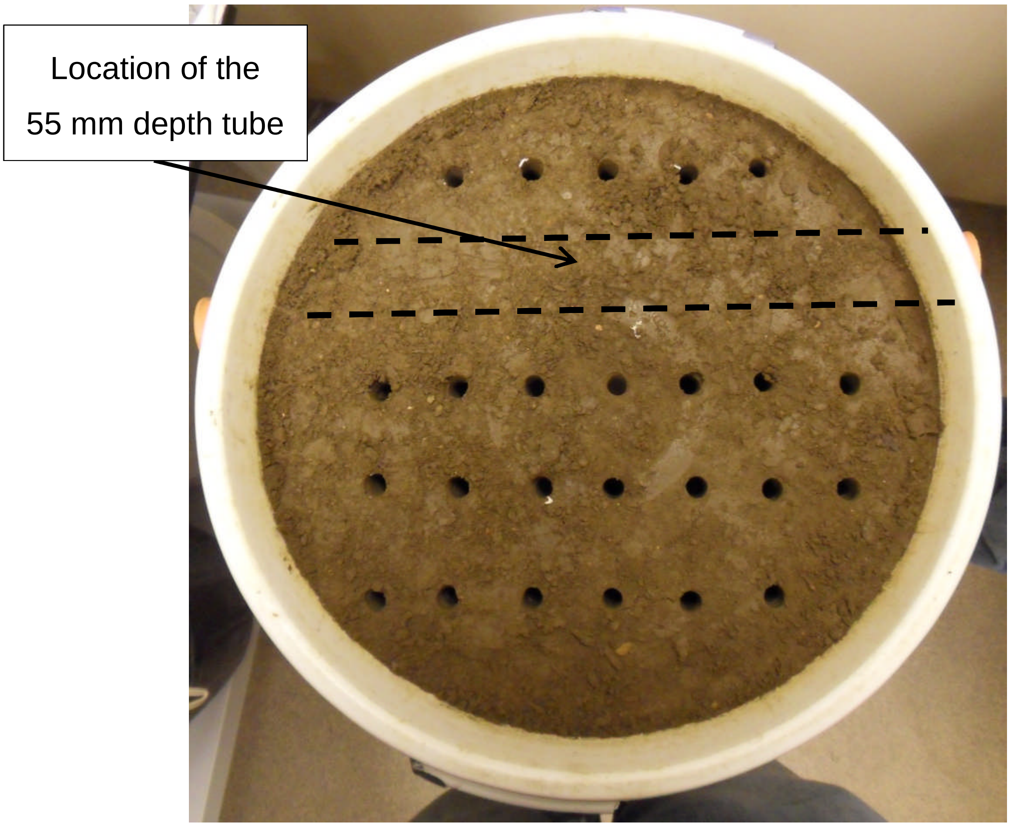


Figure 5.5 Picture of a single experimental unit looking directly down at the soil surface showing the pattern of tine holes created.

To test the diffusion characteristics the unit was sealed using a tightfitting lid (with valve) and duct tape to ensure a complete seal (Figure 5.6). The units were flushed with 100% nitrogen for a minimum of 12 hours to drive as much of the other gases present as possible from the soil. After flushing the units were left for 12 hours to equilibrate with any gas remaining in pores that could not be purged. Samples were taken from each tube prior to unsealing the unit and at regular intervals afterwards.

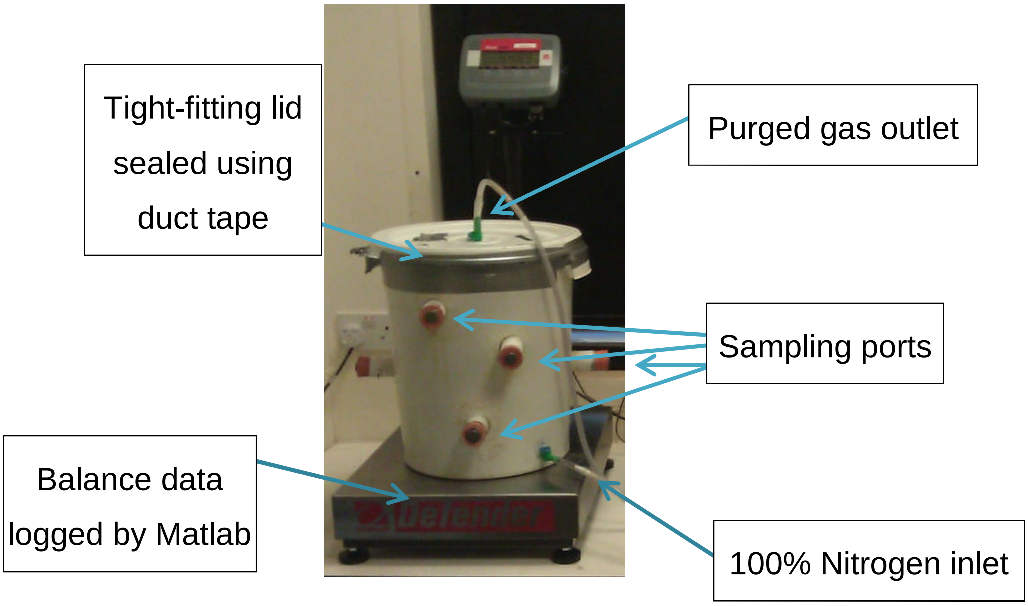


Figure 5.6 Captioned photograph of an experimental unit prepared for the flushing process in place on the balance.

Five samples were taken at approximately 90 minute intervals on the first day and then once daily for a further six days. Samples were analysed for oxygen, carbon dioxide, nitrogen, methane and nitrous oxide concentrations using gas chromatography (GC 500 Series, Cambridge Scientific Instruments) on a mixed molecular sieve/packed CTR 1 column (Grace, IL, USA) with a thermal conductivity detector (Table 5.2).

Table 5.2 Settings used for sample analysis on GC 500 Series gas chromatograph.

GC Settings	
Injector	150 °C
Column	50 °C
Detector	100 °C
Filament	320 °C
Inlet pressure	0.34 Bar

Two experimental units were prepared; each unit was flushed and allowed to equilibrate three times with no aeration. Both units were then aerated using a solid tine. The units were then examined in triplicate again.

5.3 Results

5.3.1 Effect of soil water content

Initially the trials were conducted at increased water content (26 ±1 %m). Three trials were completed under these conditions, one trial in Unit 1, and two trials in Unit 2 (Table 5.3) but were discontinued at 26 %m water content due to time constraints as the tubes at depths below 125 mm often did not show an increase in oxygen concentration after two weeks of sampling.

Table 5.3 Mean water content of the entire unit over the length of each trial Treatment A was aerated. Treatment U was unaerated.

Trial	Treatment	Unit	Gravimetric Water Content, θ (%v)	St. Error (%v)
Revised	A	1	0.23	7.53×10^{-5}
	A	1	0.23	7.11×10^{-5}
	A	1	0.23	6.61×10^{-5}
	U	1	0.23	8.38×10^{-5}
	U	1	0.23	7.82×10^{-5}
	U	1	0.24	6.34×10^{-5}
	A	2	0.23	8.09×10^{-6}
	A	2	0.24	8.65×10^{-5}
	A	2	0.23	4.71×10^{-5}
	U	2	0.23	8.56×10^{-5}
	U	2	0.24	3.01×10^{-5}
	U	2	0.23	5.92×10^{-5}
Initial	U	1	0.25	4.06×10^{-3}
	U	2	0.26	6.65×10^{-5}
	U	2	0.27	5.91×10^{-6}

Oxygen diffusion in the initial (θ=26 ±1 %m) trials was extremely slow. Even after 12 days of exposure to the atmosphere the shallowest depth in Unit 2 did not reach equilibrium with the atmosphere. In the revised (unaerated) trials (θ=23±1 %m) the top two tubes in both Units had approximately equilibrated within two days (Figure 5.7).

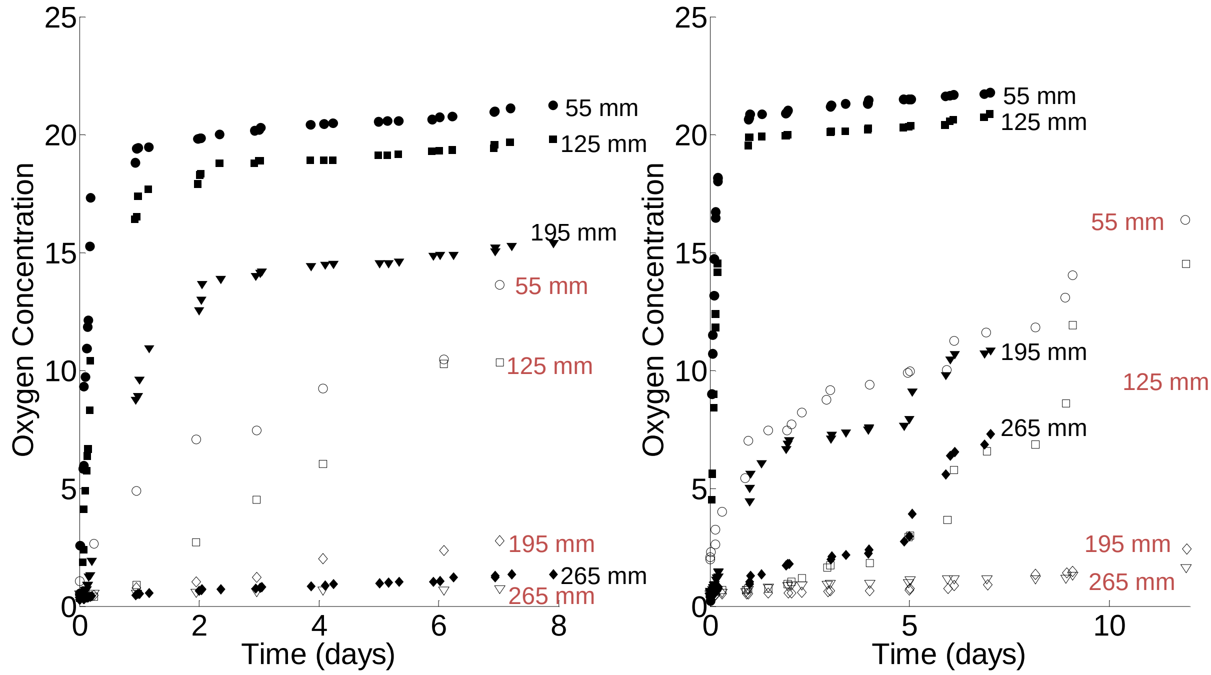


Figure 5.7 Comparison of oxygen concentrations at each depth for the initial water content (26 ± 1 %m) and revised water content (23 ± 1 %m) trials in Unit 1 (left) and Unit 2 (right). (●) 55 mm depth, (■) 125 mm depth, (▼) 195 mm depth, and (◆) 265 mm depth . Open symbols show initial trials (θ=26 ±1 %m), closed symbols show revised trials (θ=23 ±1 %m).

Comparing the initial and revised water content treatments after six days, the revised treatments all showed much greater increases in oxygen concentration than the initial water content treatment particularly at depth, where oxygen concentration was only slightly above zero for both Units over the time period (Table 5.4). The only exception was in Unit 1 at 265 mm depth where the oxygen concentration had increased markedly compared to the dry treatment. Unfortunately as these experiments were at a preliminary stage there was not a repeat measurement to compare it against – it is likely that this anomaly was caused by contamination from a worn septa. The extremely long time period required to complete each trial at 26 %m water content prevented further replicates as the effect of aeration was of greater priority in the restricted time available.

Table 5.4 Oxygen concentration increase from initial opening to six days.

Unit	θ (%m)	Oxygen concentration increase after 6 days at depth:							
		55 mm		125 mm		195 mm		265 mm	
		Mean	St. Error	Mean	St. Error	Mean	St. Error	Mean	St. Error
1	23	19.6	0.9	18.8	0.3	14.3	0.3	0.7	0.1
	26	9.4	n.a.	9.9	n.a.	0.1	n.a.	2.3	n.a.
2	23	21.0	0.3	20.1	0.1	8.1	1.1	3.7	1.4
	26	8.5	2.6	4.3	3.8	0.2	0.2	0.5	0.5

The carbon dioxide concentration was generally greater in the initial treatment than the revised (Figure 5.8). The behaviour of carbon dioxide concentration is a lot more complex as it is not originating from a single source but is dependent on the oxygen concentration at the point in soil where respiration is occurring. Any anaerobic respiration is assumed to be isotropic and negligible as no methane was detected at any point, nor were any sulphurous odours noticed.

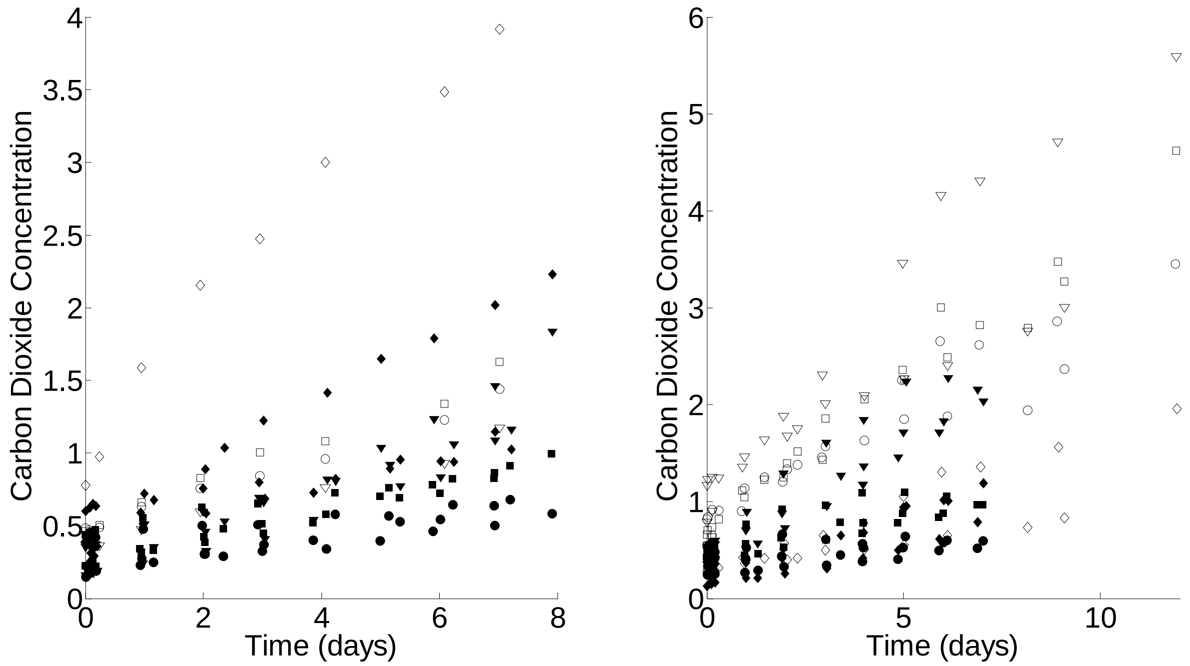


Figure 5.8 Comparison of carbon dioxide concentrations at each depth for the initial water content (26 ± 1 %m) and revised water content (23 ± 1 %m) trials in Unit 1 (left) and Unit 2 (right). (●) 55 mm depth, (■) 125 mm depth, (▼) 195 mm depth, and (◆) 265 mm depth. Open symbols show initial trials (θ=26 ±1 %m), closed symbols show revised trials (θ=23 ±1 %m).

In Unit 1 at all depths the carbon dioxide concentration is greater in the initial treatments than the revised. The greatest depth shows the largest discrepancy between treatments and the highest concentration of carbon dioxide of any point within the Unit 1 wet treatment. This is further evidence that there is a potential leak of oxygen at this depth as if all the oxygen were diffusing from the surface the greatest depth should have the lowest concentration of oxygen and a consequently lower level of aerobic respiration and therefore carbon dioxide. That the concentration of carbon dioxide is so markedly higher at this depth indicates a non-surface supply of oxygen fuelling a greater level of aerobic respiration.

Table 5.5 Carbon dioxide concentration increase from initial opening to six days after opening for initial water content and revised water content treatments

Unit	θ (%m)	Carbon dioxide concentration (%vol) increase after 6 days at depth:							
		55 mm		125 mm		195 mm		265 mm	
		Mean	St. Error	Mean	St. Error	Mean	St. Error	Mean	St. Error
1	23	0.3	0.2	0.4	0.1	0.8	0.2	0.9	0.4
	26	1.0	n.a.	1.2	n.a.	0.8	n.a.	3.1	n.a.
2	23	0.2	0.1	0.5	0.1	1.5	0.2	0.6	0.2
	26	1.6	0.5	2.1	0.3	2.3	1.1	0.7	0.3

Unit 2 has no leaks and behaves as expected. In the revised treatment near the surface at 55 mm there is a lower level of carbon dioxide despite the highest level of oxygen due to the ability for the carbon dioxide to escape relatively easily from this depth to the surface. At greater depths carbon dioxide concentrations increase despite lower oxygen contents. It is likely almost all the oxygen is consumed as it arrives and the carbon dioxide evolved cannot escape to the outside atmosphere as easily and accumulates. At the greatest depth the oxygen supply is so restricted that little or no aerobic respiration is possible, carbon dioxide concentrations in this area are more likely to have evolved higher in the profile and diffused to this depth.

For the sake of expediency the lower water content was used for the remainder of the trials.

5.3.2 Diffusion of oxygen in the soil

The results were analysed using repeated-measures ANOVA in Statistica 10 (Statsoft, USA). The repeating-measure was time, taken at 0,1,2,3,4,5,6, and 7 days from exposure to atmosphere. The remaining factors were depth, Unit, and treatment.

When examining the average of the two Units over time, the general trend is of reducing oxygen concentration with increasing depth for all points in time as expected. As time increased the oxygen concentration at all depths increased until equilibrium was reached or the experiment was stopped. Aeration was found to significantly increase the concentration of oxygen in the soil profile compared to an untreated profile ($p<0.05$) by approximately 1.5% on average over time.

5.3.2.1 Difference between Units

The behaviour of both Units was not significantly different for depths 55 mm and 125 mm in both aerated and unaerated treatments. Below these depths their behaviour deviates considerably (Figure 5.9). In Unit 1 a greater concentration of oxygen is observed at 195 mm depth than in Unit 2 for each time period. At 265 mm this trend is reversed with 0.9%v oxygen in Unit 1 and 4.4%v oxygen after seven days. The same trend is observed in the aerated treatments where the difference between the two Units becomes slightly greater at the lower depths.

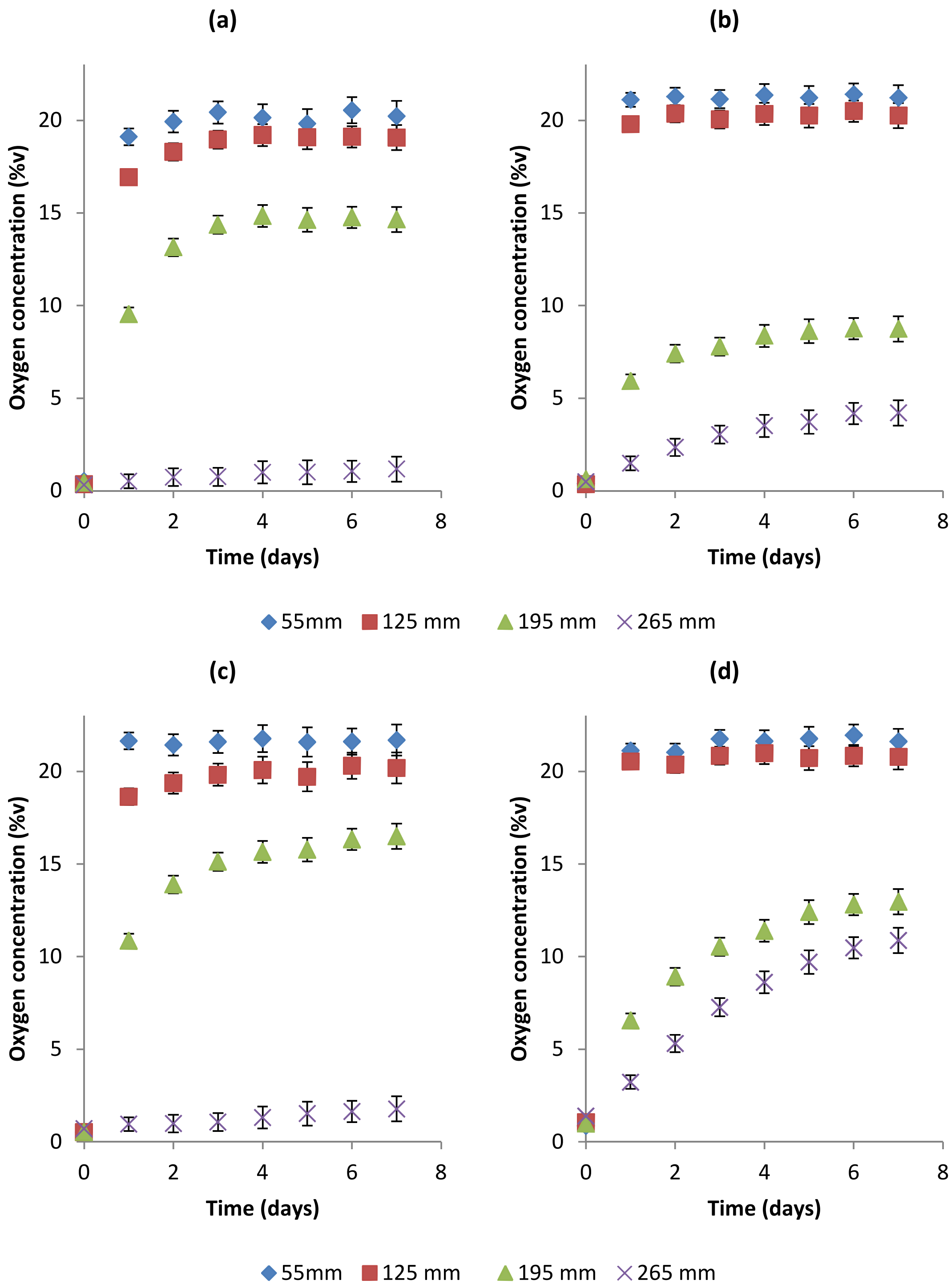


Figure 5.9 A comparison of the oxygen concentrations at each depth for Units 1 (a) and Unit 2 (b) without aeration and Units 1 (c) and Unit 2 (d) with aeration Vertical bars denote standard error.

5.3.2.2 Effect of aeration

Aeration did not significantly affect the oxygen concentration at 55 mm and 125 mm ($p<0.05$) in either Unit. In Unit 1 the oxygen concentration at 195 mm is only significantly different ($p<0.05$) between aerated and unaerated treatments after 6 days (Figure 5.10). The 265 mm depth shows no treatment effect at any time Unit 2 at 195 mm there is an aeration treatment effect from 3 days onwards with increased oxygen concentration as a result of aeration. At 265 mm aeration causes significantly increased oxygen concentrations after 2 days.

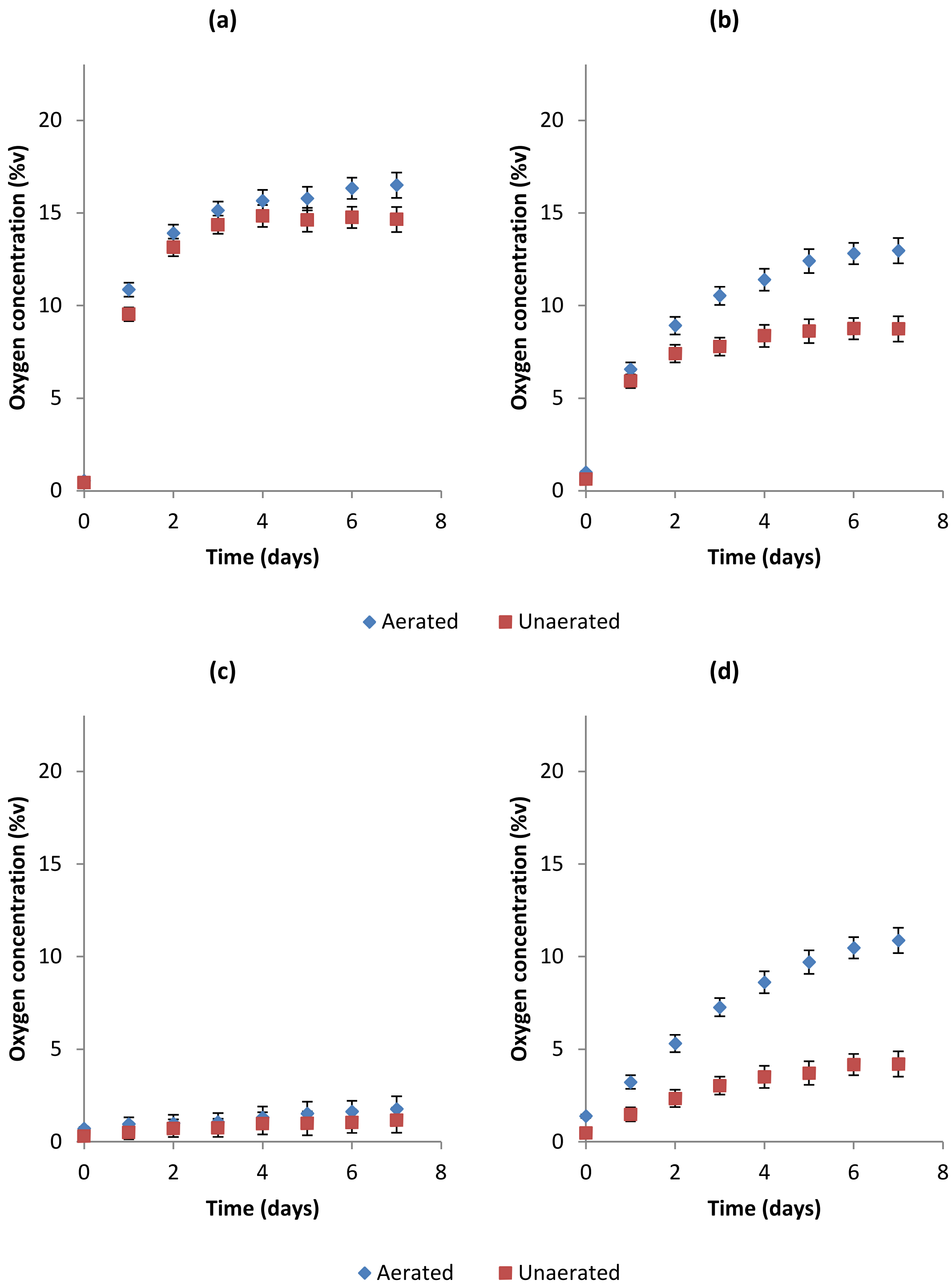


Figure 5.10 A comparison of oxygen concentration over time for aerated and unaerated trials in Unit 1 (a) and Unit 2 (b) at 195 mm depth, and Unit 1 (c) and Unit 2 (d) at 265 mm depth. Vertical bars denote standard error.

5.3.3 Evolution and diffusion of carbon dioxide in the soil

An unfortunate complication is the respiration of soil microbes. Oxygen is consumed in aerobic respiration and carbon dioxide evolved as a waste product. Microbial respiration is relatively low with the maximum recorded concentration of 2.2%v of carbon dioxide at 195 mm, Unit 2, after seven days.

There is a significant aeration treatment effect ($p<0.05$). The average concentration of carbon dioxide over the whole time period in the unaerated trials was 0.73%v and, in the aerated treatments, 0.9%v. It is possible that the elevated level in the aerated treatments is due to a higher starting point as the average carbon dioxide concentration for the two treatments converges to the same value after seven days of approximately 1%v.

The two units show very similar carbon dioxide profiles. The concentrations at 55 mm and 125 mm are very similar and any differences are removed over time as the values converge. Similarly at 265 mm the profiles initially diverge but then converge over time to a similar value. At 195 mm the concentration of carbon dioxide in Unit 2 is much larger than in Unit 1 and increases more rapidly over time at a rate of 0.22 %v day^{-1} compared to 0.14 %v day^{-1} respectively (Figure 5.11).

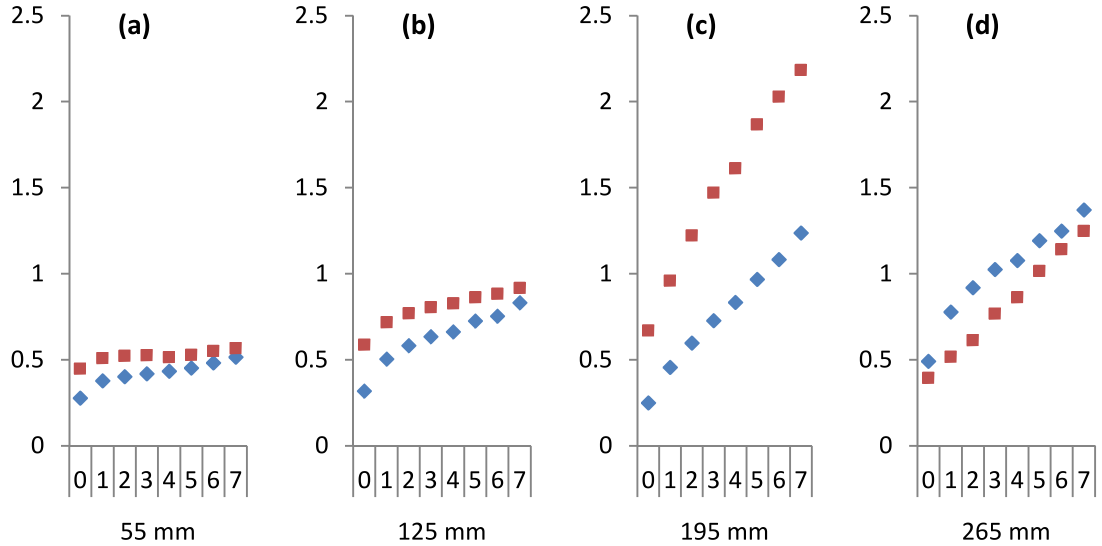


Figure 5.11 A comparison of carbon dioxide concentrations in Unit 1 (■) and Unit 2 (◆) over time at 55mm (a), 125 mm (b), 195 mm (c) and 265 mm (d) depths.

5.3.4 Numerical Analysis

The experimental data for each depth was normalised by dividing by atmospheric oxygen concentration and fitted to an exponential curve (Figure 5.12) of the form:

$$\frac{C_{(x,t)}}{C_0} = \mathrm{M}e^{Nt} + Pe^{Qt} \tag{5.9}$$

Where $C_{(x,t)}$ is the concentration at depth x and time t, C_0 is the atmospheric concentration of oxygen and M, N, P and Q are fitted constants. Each fitted curve had a regression coefficient of 0.98 or above (Table 5.6).

The fitted equations were then used to calculate the concentration at each depth for specific times as required by the Crank-Nicolson scheme.

$$\frac{C_j^{n+1} - C_j^n}{\Delta t} = \frac{D}{2}\left\{\frac{\left(C_{j+1}^{n+1} - 2C_j^{n+1} + C_{j-1}^{n+1}\right)}{(\Delta x)^2} + \frac{\left(C_{j+1}^{n} - 2C_j^{n} + C_{j-1}^{n}\right)}{(\Delta x)^2}\right\} \tag{5.10}$$

The Crank-Nicolson scheme for solving the one-dimensional diffusion equation was chosen as it is unconditionally stable.

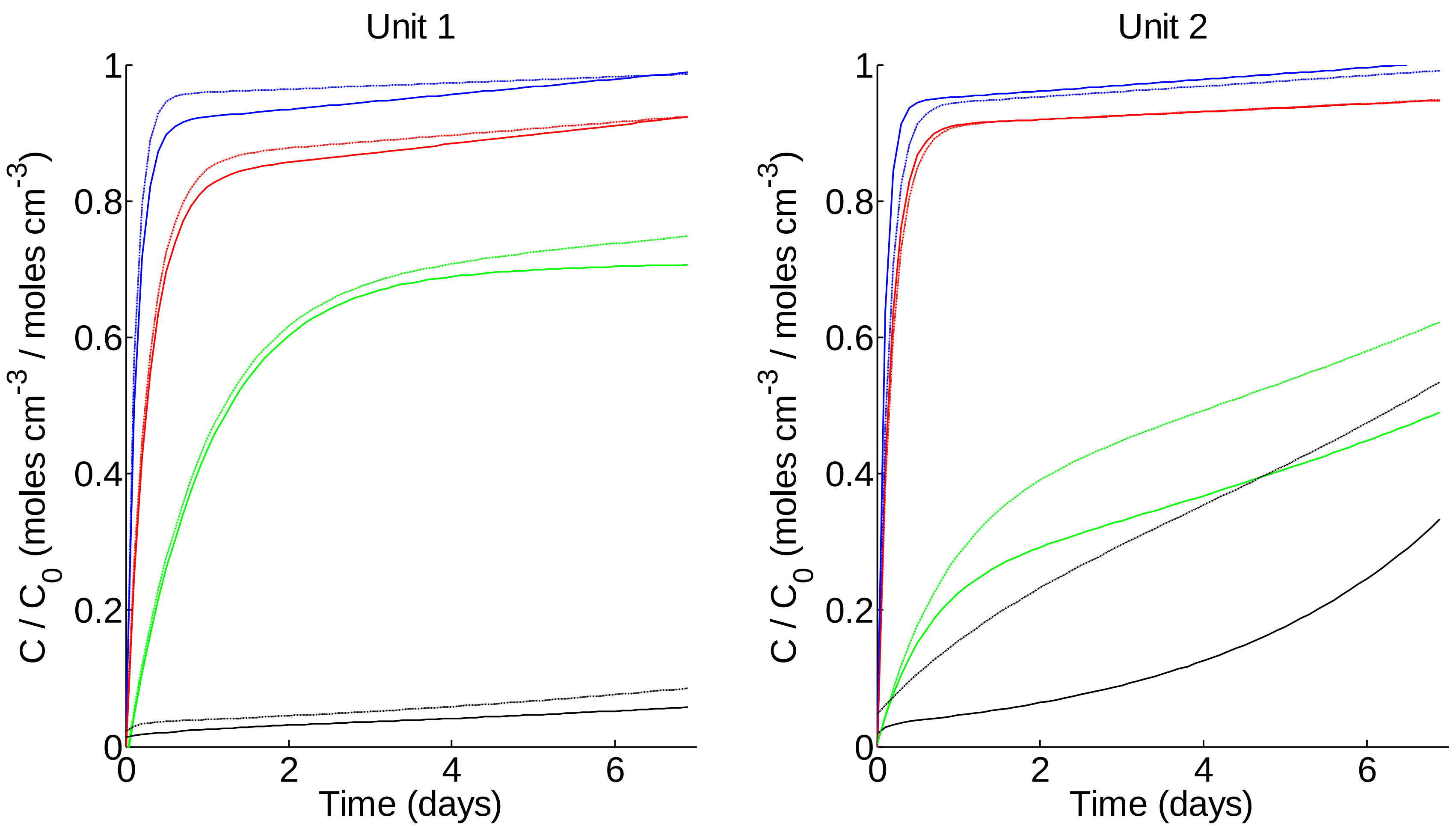


Figure 5.12 Fitted curves representing the unaerated and aerated trials for Units 1 and 2. Solid lines represent unaerated results, dashed lines show aerated results. ● 55 mm, ● 125 mm, ● 195 mm, ● 265 mm.

Table 5.6 Values of the coefficients of the fitted curves for each depth, treatment and unit.

Unit	Treatment	Depth (mm)	Co-efficient				Goodness of fit	
			M	N	P	Q	Adjusted R^2	RMSE
1	Unaerated	55	0.91	0.01	-0.87	-7.41	0.99	0.04
		125	0.83	0.02	-0.83	-3.54	0.99	0.03
		195	0.69	0.00	-0.72	-1.01	0.99	0.02
		265	0.03	0.12	-0.01	-1.19	0.99	0.00
	Aerated	55	0.96	0.00	-0.93	-8.75	0.99	0.02
		125	0.86	0.01	-0.85	-3.60	1.00	0.02
		195	0.68	0.01	-0.69	-1.08	1.00	0.02
		265	0.03	0.13	-0.01	-7.45	0.98	0.00
2	Unaerated	55	0.94	0.01	-0.92	-11.03	1.00	0.01
		125	0.91	0.01	-0.91	-6.06	1.00	0.02
		195	0.25	0.10	-0.24	-1.61	0.98	0.02
		265	0.03	0.34	-0.01	-7.47	0.96	0.02
	Aerated	55	0.94	0.01	-0.94	-6.96	0.98	0.04
		125	0.91	0.01	-0.90	-5.38	0.98	0.04
		195	0.36	0.08	-0.36	-1.18	0.99	0.02
		265	0.22	0.13	-0.17	-0.58	0.99	0.02

The results of the Crank-Nicholson scheme were poor. The solution was highly dependent on the time step chosen (Table 5.7). Given the very slow rate of diffusion the extremely small rate of change in concentration the concentrations remain effectively constant so that when the time step is varied, as in Table 5.7, the value of the diffusion coefficient is adjusted by the inverse of the factor change in time.

Table 5.7 Mean value of diffusion coefficient over the whole time period using different time intervals.

Unit	Treatment	Depth (mm)	Mean over time of diffusion coefficient (cm2 s-1)		
			0.1 days	0.01 days	0.001 days
1	Unaerated	125	-0.0054	-0.053	-0.53
1	Unaerated	195	-0.006	-0.059	-0.59
1	Aerated	125	-0.0061	-0.061	-0.61
1	Aerated	195	-0.0056	-0.055	-0.55
2	Unaerated	125	-0.0012	-0.012	-0.12
2	Unaerated	195	0.0194	0.193	1.93
2	Aerated	125	-0.0009	-0.0092	-0.09
2	Aerated	195	0.016	0.159	1.59

Over time the values of the diffusion coefficient were found to vary wildly (Figure 5.13 and Figure 5.14).

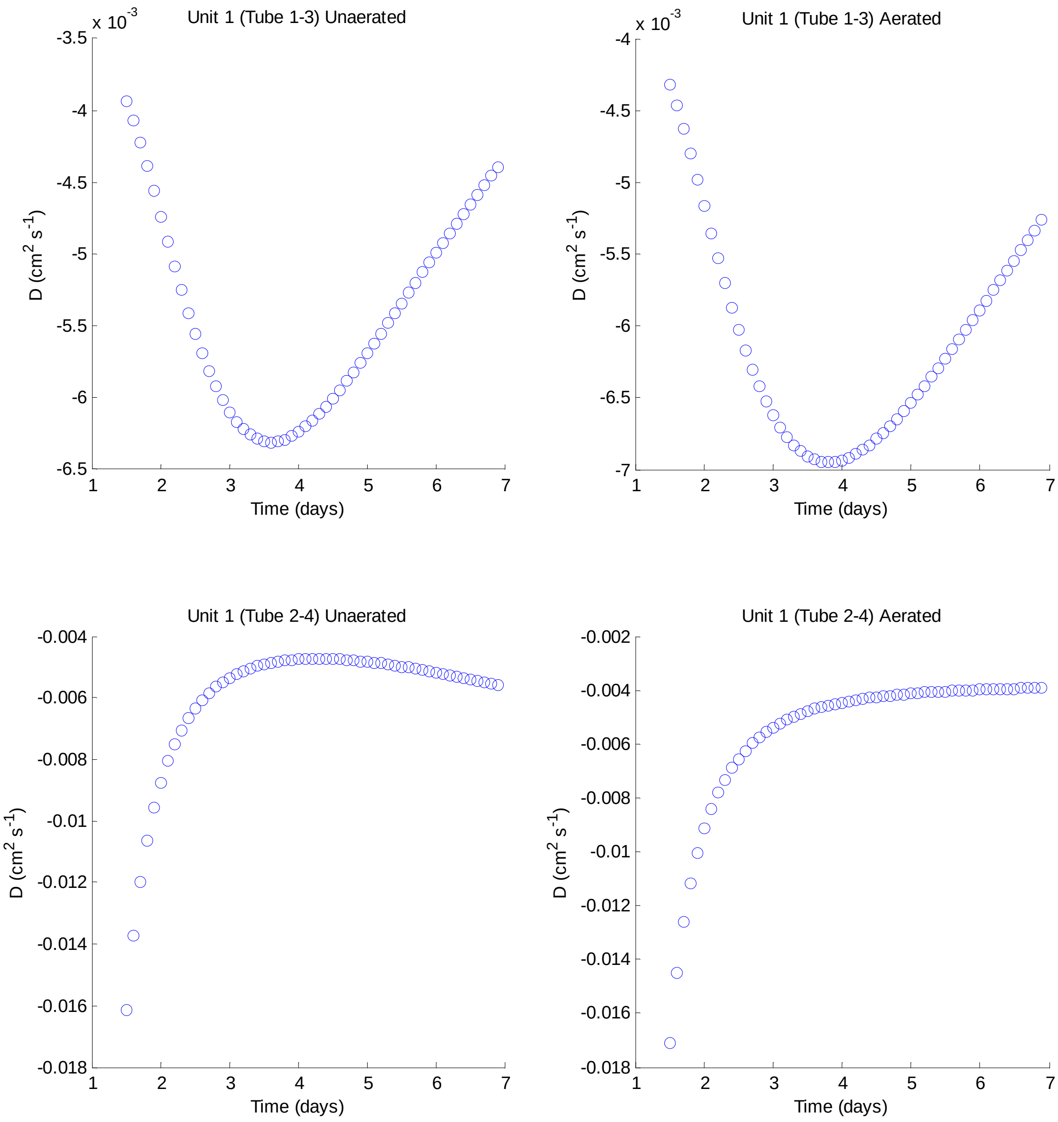


Figure 5.13 Diffusion coefficient calculated over time for 125 mm and 195 mm depth in Unit 1 for Unaerated and Aerated treatments using 0.1 days as the time step in the Crank-Nicholson finite difference scheme.

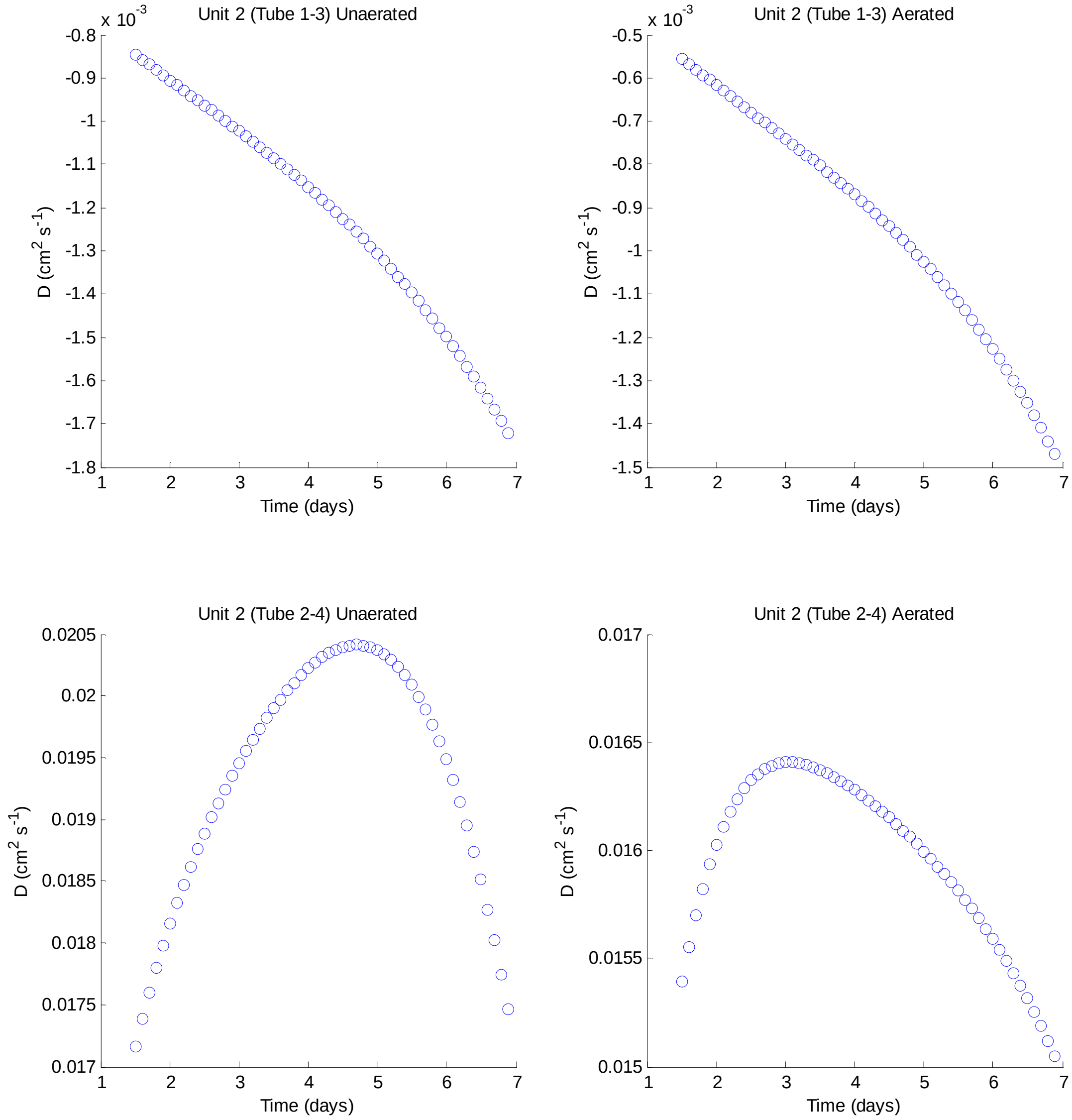


Figure 5.14 Diffusion coefficient calculated over time for 125 mm and 195 mm depth in Unit 1 for Unaerated and Aerated treatments using 0.1 days as the time step in the Crank-Nicholson finite difference scheme.

The value of the diffusion coefficient is expected to vary slightly with concentration due to the changing mole fractions of the soil air constituents. The diffusion coefficient should slightly increase as oxygen concentrations increase (Figure 5.15). The expected change in the soil would be much smaller given the vastly reduced diffusion coefficient expected due to the restrictions imposed by the pore network.

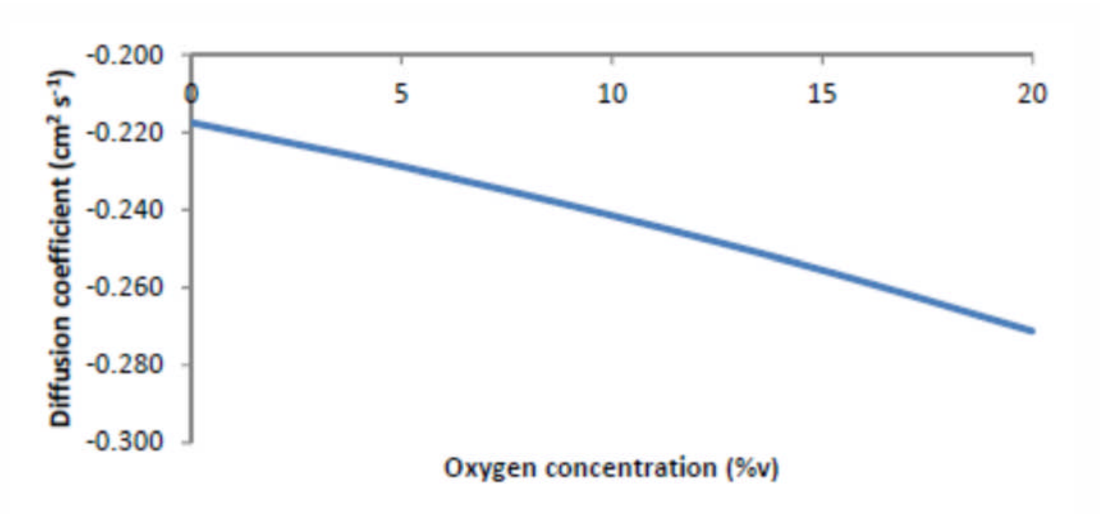


Figure 5.15 Calculated diffusion coefficient of oxygen in a nitrogen dominated gas mix at 100% relative humidity and a constant 2% carbon dioxide concentration with changing oxygen concentration.

Only the values of diffusion coefficient at 125 mm in Unit 2 appeared to follow the expected trend, however given the dependence on the time step chosen the interpretation of the results is very subjective given that any result required can be achieved by changing the time step.

Overall this method seems unsuitable for this analysis.

5.4 Discussion

5.4.1 Effect of soil water

Water films effectively block gas diffusion (Stępniewski and Gliński, 1985) as soil water increases the tortuosity increases and connectivity decreases in the pore network. The initial trials (26±1%m) showed drastically reduced rates of diffusion compared to revised trials run at 23±1%m (Figure 5.7). This behaviour is entirely expected given the effective barriers that are formed by water filled pores (Stępniewski and Gliński, 1985). Thus the greater the water content the greater the tortuosity of the pore network for oxygen transfer until at some critical point gas diffusion is effectively stopped. Whilst that point has not been reached in these experiments the rate of gas diffusion is very slow. The change in water content may appear small, the equivalent volumetric water content is 40.3 %v in the initial trials and 35.7 %v in the revised trials so represents an decrease in water filled porosity of 11.5% but given that the water-filled pores will empty in an order inverse to the pore size (i.e. larger pores will empty before smaller pores) this small reduction in water content could represent the opening of a considerable extent of the larger diameter pore network for gas exchange thus greatly increasing connectivity and decreasing tortuosity.

5.4.2 Diffusion of oxygen in the soil

5.4.2.1 Differences between Units

The existence of a diffusion barrier in Unit 1 in the soil profile somewhere below 195 mm and above 265 mm deep could explain the discrepancy between the oxygen concentrations over time in Units 1 and 2. The barrier could be formed from a particularly dense layer of soil or potentially where the layers during construction of the soil profile failed to bond. The near complete lack of oxygen diffusion to 265 mm and the elevated oxygen concentrations at 195 mm in Unit 1 compared to Unit 2 provide further evidence of this. A diffusion barrier in the soil profile is akin to raising the bottom of the bucket to that height. Oxygen cannot diffuse through it, hence no oxygen diffusion to 265 mm. The diffusion of oxygen into the soil can be pictured almost as a wave rolling into the soil where the concentration before and at the wave front is zero and behind it, greater than zero. When the wave front reaches the diffusion barrier (or the base of the bucket in Unit 2) the diffusing oxygen can go no further. The wave analogy breaks down at this point but the effect can be imagined as similar to reflection. Figure 5.16 shows two numerical solutions to Equation (5.3) where the distance from surface to boundary (L) is changed. As expected in the unit where the L=1 the rate of oxygen concentration increase is slower for all depths than in the shorter system, particularly at depth. For this reason the build-up of oxygen at depth 195 mm in Unit 1 is much more rapid than in Unit 2 where the boundary is at 350 mm.

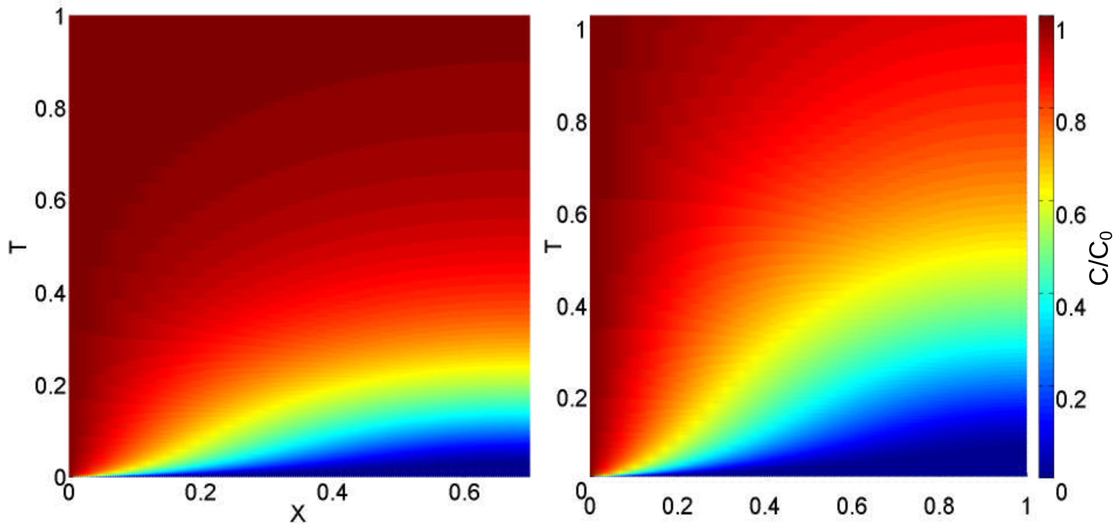


Figure 5.16 Normalised oxygen concentration (C/C_0) numerical solutions to Equation (5.3) for a finite system over time, T, and distance, X, for a large system (L=1) and a smaller system (L=0.7). $0 < X < 0.7$ (left) and $0 < X < 1$ (right).

Upon examination of the soil profile a thin layer was found at approximately 240 mm depth (Figure 5.17). Below this layer the soil was darker in colour, displaying typical symptoms of anoxia or high water content.

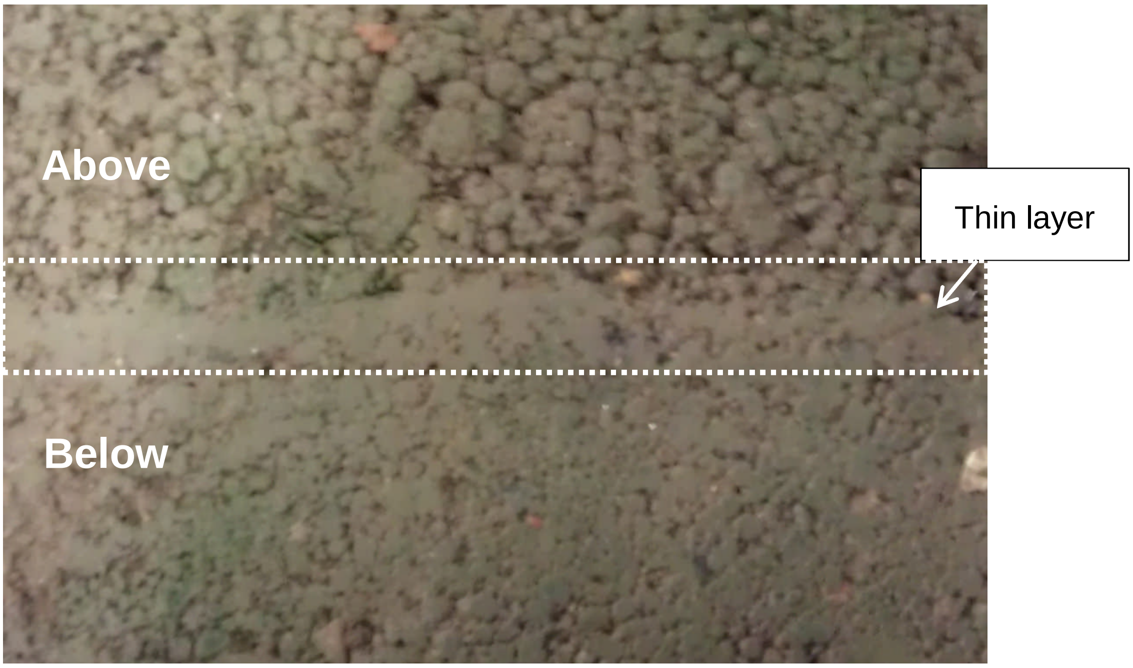


Figure 5.17 Photograph of a section of soil showing a thin layer of tightly compressed soil that may be acting as a barrier to diffusion in Unit 2.

5.4.2.2 Effect of aeration

Aeration significantly increased the rate of oxygen diffusion into the soil but the difference was small. Between 0-125 mm depth the rate of diffusion is so rapid that aeration had no discernible effect. Unfortunately the analysis was not possible on the results between 0-1 days as the time steps between points was not consistent in all the trials. It is possible that at time steps smaller than a day a significant difference could have been found between the aerated and unaerated treatments at the shallower depths. The fitted curves in Figure 5.12 show slight deviations between aerated and unaerated soils but it is not possible to tell if these are statistically significant.

The effect of aeration in Unit 1 was to raise slightly the rate of oxygen increase at 195 mm, but had no significant effect on the oxygen concentration at 265 mm. This is consistent with the diffusion barrier hypothesis. The fact that it takes six days before the unaerated and aerated treatments become significantly different indicates that the barrier is probably nearer to 265 mm deep than 195 mm so it is most likely the layer found at ~240 mm.

Aeration significantly increases the oxygen concentrations over time for both the 195 mm depth and the 265 mm depth in Unit 2. The rate of increase at 265 mm outstrips the rate at 195 mm and the curves begin to converge. Two contributing factors lead to this. The first is reflection at the boundary causing a flattening of the concentration over depth so the two curves are expected to converge over time (Figure 5.18). The second reason is microbial respiration which peaks at 195 mm indicated by the maximum carbon dioxide concentration occurring here (2.2%v, Figure 5.11). Greater respiration leads to increased consumption of oxygen at this depth than at 265 mm.

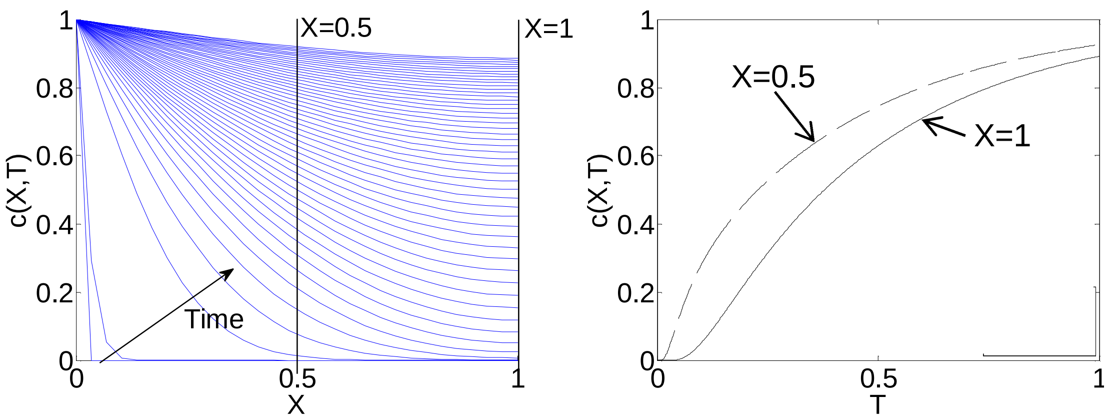


Figure 5.18 Numerical solutions to Equation (5.3) illustrating the gradual flattening of the concentration-distance curves over time (left) such that the concentrations at two distinct depths will converge over time (right).

5.4.3 Evolution and diffusion of carbon dioxide in the soil

The carbon dioxide concentration in the soil was generally much smaller than the concentration of oxygen indicating that the supply of oxygen is generally much greater than the oxygen consumed in respiration.

For both Units, at each depth, before the soil was exposed to the atmosphere carbon dioxide concentrations were approximately 0.5%v. Potentially this could be produced from the respiration of a small amount of oxygen that was not purged from the system in very small or isolated pores. The uniformity of the initial distribution of carbon dioxide concentrations means that the entrapped oxygen must also be uniformly distributed so it seems more likely given the heterogeneous nature of the soil that this represents a background anaerobic respiration level of approximately 0.04%v CO_2 h^{-1}.

The effect of aeration on carbon dioxide concentrations was a slight raise when averaged over the whole time period. Examining the time*treatment effects the elevated carbon dioxide in the aerated treatment overall is a consequence of an elevated starting concentration compared to the unaerated treatments and the two values converge over time to approximately 1.1%v over the whole profile.

The individual depths for each Unit are not significantly different in carbon dioxide concentrations over time except for 195 mm. In Unit 2 the carbon dioxide concentration increase much more rapidly than in Unit 1 at this depth due to the increased supply of oxygen due to shallower lower boundary, as in Figure 5.18, resulting in increased respiration.

5.4.4 Method limitations

Fick's second law strictly only applies to the movement of gas in a binary system without physical barriers and its effectiveness in describing these systems has been questioned (Webb and Pruess, 2003). The finite difference method is first and foremost an approximation and so will introduce an element of error and does not seem to function at all in these circumstances.

To improve the accuracy of these findings it is suggested that the concentration be monitored more frequently in time (and space if possible). The use of gas sensors would allow for automatic measurement instead of the very time consuming and user intensive method of gas chromatography. The fast autonomous nature of the sampling should allow for a higher resolution in time both in and out of normal working hours. Automatic logging should also allow for simultaneous measurements at all depths. Automation should allow for a more thorough examination of various factors, such as, soil water, changing bulk density and alternative aeration treatments as the experiment can effectively be left to run itself unlike the current method where user availability was a limiting factor.

More advanced models of gas diffusion in media could be used in place of Fick’s law, such as the dusty-gas model however the equations are far more complex and difficult to implement (Webb and Pruess, 2003). The dusty-gas model uses the kinetic theory of gases to predict the movement of gases through the porous material, in this case the soil, which is included in the model as large immobile gas molecules through which the gas being examined is diffusing.

The use of argon as the diffusing gas of measurement would eliminate the complication of microbial respiration consuming oxygen and releasing carbon dioxide.

Solutions to the diffusion equation exist for the boundary conditions of the experiment (Stępniewski and Gliński, 1985). However, for an exact solution two unknowns must be established. One is the behaviour of the respiration in the soil and how it relates to oxygen concentrations. The second is the value of the diffusion coefficient. If argon were used instead of carbon dioxide the equations are a lot simpler as there is no consumption term. Fitting these equations to the result should allow for the calculation of the diffusion coefficient in the soil and the effect of aeration on it.

5.5 Conclusion and relevance to cricket

O'Neil and Carrow (1983) found that the oxygen diffusion rate was reduced drastically by irrigation in compacted sandy soils and can negatively impact healthy turf growth. The slower draining, finer-textured clay soils used in most cricket pitches would be even worse. The trials at elevated water contents demonstrate very well the dramatic reduction in oxygen diffusion due to water films and water filled pores. Most aeration techniques in cricket pitches must wait until the soil is wet enough that the soil strength has diminished to the point where the machines can penetrate easily into the soil. As a result the water contents of these soils are expected to be very high at the time of treatment, in Section 7 the water content measured during treatments was in excess of 30%m. Assuming that diffusion was not completely blocked by water, the movement of oxygen through such wet soil must be very slow. Coupled with compaction and smearing around the tine hole and the relatively modest effect of aeration on diffusion in much dryer soils it would seem that as a process for improving the oxygenation status of the soil it would only be effective within a close distance to the tine hole itself. If the tine hole persists as the soil dries and very local shrink-swell creates fissures that increase localised porosity this could increase the effective distance. Overall it is better to have tine holes closely spaced so that in aggregate the localised effects can improve the general oxygenation status of the soil. As most compaction occurs at the base of the tine hole it can be expected that diffusion through that part is greatly impeded, so gas exchange is unlikely to be facilitated much beyond the depth of the tine hole.

Compaction around the tine hole during aeration with solid and hollow tines (Rieke and Murphy, 1989; Murphy *et al.*, 1993; Petrovic, 1979) has been noted as a possible cause of a hard pan in the soil if these treatments are routinely applied to the same depth (Rieke and Murphy, 1989). The effect of a hard pan on oxygen diffusion is illustrated by Unit 1 with little or no oxygen penetrating through the barrier. The effect of a sub-surface compacted layer restricts root growth beyond that depth, encourages shallow rooting (increasing thatch) (Matthieu *et al.*, 2011; Agnew and Carrow, 1985) contributing to plant stress as a shallow densely rooted soil is more likely to suffer periods of highly restricted oxygen diffusion (Carrow, 2003).

A modest change in soil water content led to a large change in the rate of oxygen diffusion into the soil compared to the modest change induced by aeration. Preventing soil water content from getting too great could be more effective at maintaining healthy gas exchange than mechanical aeration.

5.6 Diffusion with Grass

The same experiment was conducted on units seeded with perennial ryegrass (*Lolium perenne*) as part of a Master's degree project undertaken by Katie Wright in 2010. The experimental method and conclusions are summarised here together with suggestions for improving the experiment.

5.6.1 Method

The basic method was the same as above with two exceptions. The grass experiments the units were seeded with PM36 Wicket at 75 g m^{-2} and fertilised with Granusports SRF 4:2:3 N:P:K at 30 g m^{-2}. The grass was left to mature for eight weeks before testing. Secondly, the units were watered daily based on the measurement of total mass to an accuracy of ±100g, corresponding to approximately ±2.5%m gravimetric water content. Otherwise methods were the same as above.

5.6.2 Summary of Results

The grassed units were maintained and tested by Katie Wright as part of a Master of Science degree and analysed using rates of change in oxygen concentration (Wright, 2010). The results showed much more variability in oxygen concentrations compared to the bare soil experiments (Figure 5.19). Most of the grass died as a result of the flushing process. The much greater level of respiration due to the remaining grass roots and microbial activity on the dead roots resulted in much higher carbon dioxide concentrations and consequently much greater consumption of oxygen. The maximum carbon dioxide concentration occurred at depth 195 mm and average root depth was 150 mm. The daily watering to such a low degree of accuracy led to sometimes large volumes of water being added. This had the effect of causing waves of oxygen depletion as water acts as a barrier to oxygen diffusion.

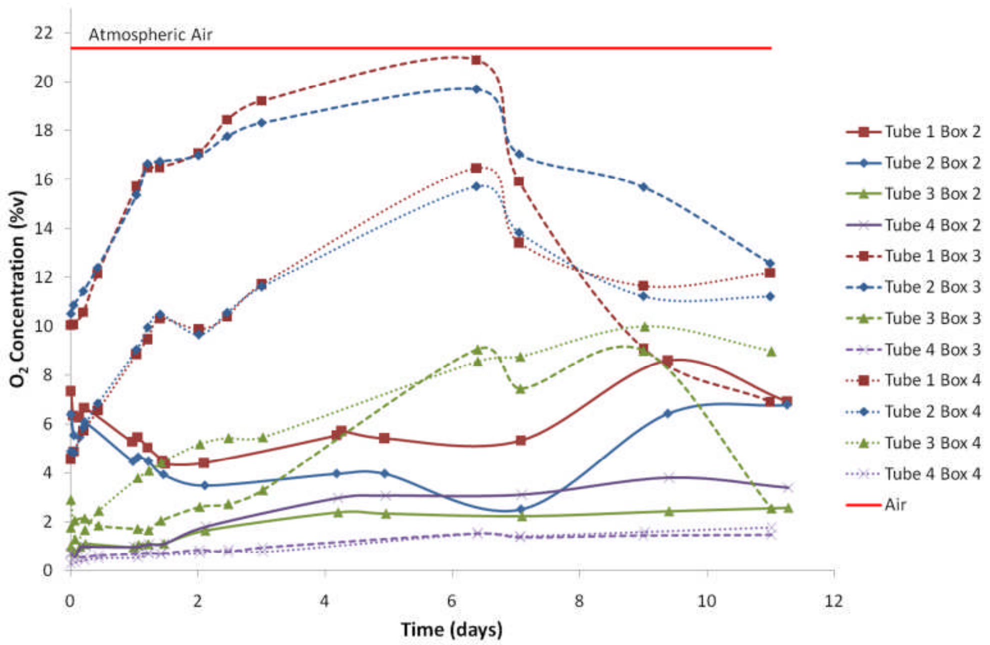


Figure 5.19 Oxygen concentration with time for three grassed units. Tube 1 is at 55 mm depth, Tube 2 at 125 mm, Tube 3 at 195 mm and Tube 4 at 265 mm.

The aerated treatments showed a significant effect on reducing carbon dioxide concentrations but did not significantly improve oxygen concentrations. Moisture content was identified as critical to the diffusion process within the soil with high moisture contents leading to the production of nitrous oxide and methane as a response to low oxygenation conditions.

The practise of routinely flooding the pitch was identified as potential source of generating anaerobic conditions within a pitch and was strongly discouraged. Due to the large degree of variation only limited conclusions could be drawn. Further work was suggested, with modifications to the existing method including increased accuracy of water content control, to examine other treatments than solid tine aeration.

5.6.3 Method limitations and suggested improvements

The most significant problems with the grassed units were moisture content control and the nitrogen flushing. The problem with the moisture content control was addressed in the bare soil units by using more accurate balances. In the bare units it was also suggested that argon be used as the measurement gas rather than oxygen due to microbial respiration utilising oxygen. In the case of the grassed units this is even more important but oxygen must still be maintained in the system so that the viability of the grass plant and organisms is retained. In place a gas mix should be used containing at least 21% oxygen which includes a known amount of argon. Flushing the units with this gas and then measuring the depletion of argon in the system would provide a quantifiable measure of the diffusion properties of the soil without killing the grass plant. The advantage of measuring depletion rather than build-up is that to measure the build-up of argon would require that the atmosphere above the soil be maintained at a constant argon concentration usually achieved by continually flushing the headspace with a known gas mix. With such slow diffusion, experiments lasting several weeks this would represent considerable expense in custom gas mixes.

6 Effect of bulk density and solid tine aeration on root growth and microbial biomass

Increasing soil bulk density was found to profoundly reduce shoot growth and marginally reduce root density in a clay soil. Increasing bulk density caused a corresponding rise in root density in shallow layers of soil and a reduction in deeper layers. Microbial biomass generally followed the same trends as root density and was reduced by soil compaction. Solid tine aeration was shown to increase root density but only at the highest bulk density (1.90 g cm^{-3}) and did not increase the depth of root penetration.

6.1 Introduction

A cricket pitch must be hard to maximise energy restitution in ball-surface interactions and durable enough to last a whole game (or several games at club or school level). Consequently the soil has a high dry bulk density which is not directly compatible with the ideal growing condition of the turfgrass plant. The playing characteristics of the cricket pitch are not determined by the soil alone as the grass plays an important role. Above-ground the grass plant affects ball speed and trajectory and the relative accessibility provides much easier management by Groundsmen. Below ground the root system is somewhat more inaccessible and difficult to manage but plays a key role in the mechanical and hydrological characteristics of the pitch (Section 2).

In agricultural systems, increased compaction was found to cause a decrease in the development of plant roots (Boone and Veen, 1994). Typically, the majority of turf grass research is in sandy soils (for golf) and much of it aimed at finding the root-limiting bulk density in those soils. Common in the literature is a general trend of decreasing root density with depth (Baker *et al.*, 1998b; Shipton, 2008; O'Neil and Carrow, 1983; Matthieu *et al.*, 2011; Cook *et al.*, 1996), and decreased shoot growth (Cook *et al.*, 1996; Carrow, 1980) with increasing compaction. Reported effects of soil compaction on total root mass were conflicting with reduction in root mass found by Cook *et al.* (1996) and no effect found by Shipton (2008) and Matthieu *et al.* (2011). Agnew and Christians (1993) found hollow core aeration had no effect on root density.

Previous work on two typical cricket soils at a range of densities from 1.20–1.85 g cm^{-3} indicated that soil type differences affected root growth more than density (Shipton, 2008). Baker *et al.*, (1998b) counted roots rather than weighed them so could not compare total root mass in the system but found decreasing numbers of roots with depth in line with the general reported trend.

In Shipton (2008) both the top and bottom of the soil mass were exposed to the atmosphere and so available for gas exchange (Figure 6.1).

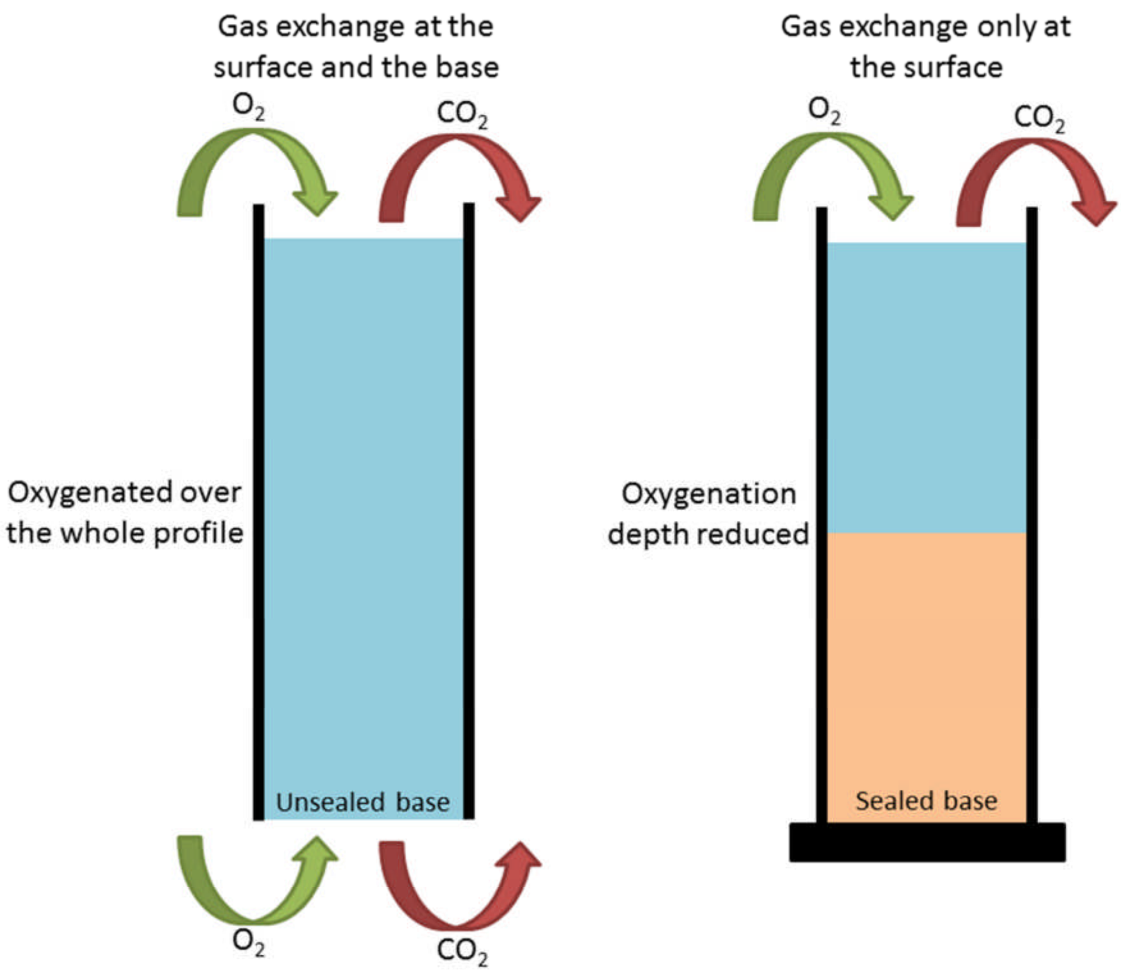


Figure 6.1 Diagram to illustrate the effect of a sealed and unsealed base in experimental units.

Because of this, the experiment may not exhibit the symptoms of restricted gas exchange experienced in the field. This experiment using units similar to Shipton (2008) will examine the effect of restricted gas exchange by comparison of soil cores open only at the surface (sealed units) and soil cores open at both the base and surface (unsealed units) for gas exchange with the atmosphere. It is hypothesised that high density soils will retard root growth due to poor gas exchange in the sealed units compared to the unsealed units. A second experiment will examine the effect of aeration on the sealed units. It is expected by the creation of large artificial macropores that aeration will positively influence root growth through increased gas exchange (Section 5).

6.2 Experimental Approach

Samples were prepared in September-October 2010 by evenly packing Soil BC (Section 4) into tubes 104 mm internal diameter by 335 mm height. The three dry bulk density targets were 1.20 g cm^{-3}, 1.55 g cm^{-3} and 2.00 g cm^{-3}. Unfortunately achieving 2.00 g cm^{-3} proved to be extremely difficult as the pressure required to compress the soil to this density caused the tubes to rupture. 1.90 g cm^{-3} was established as an achievable upper bulk density. The three treatments were:

A - Unsealed at the base and not aerated.

B - Sealed at the base and not aerated.

C - Sealed at the base and underwent simulated solid tine aeration.

Each treatment and density was replicated five times. (Figure 6.2).

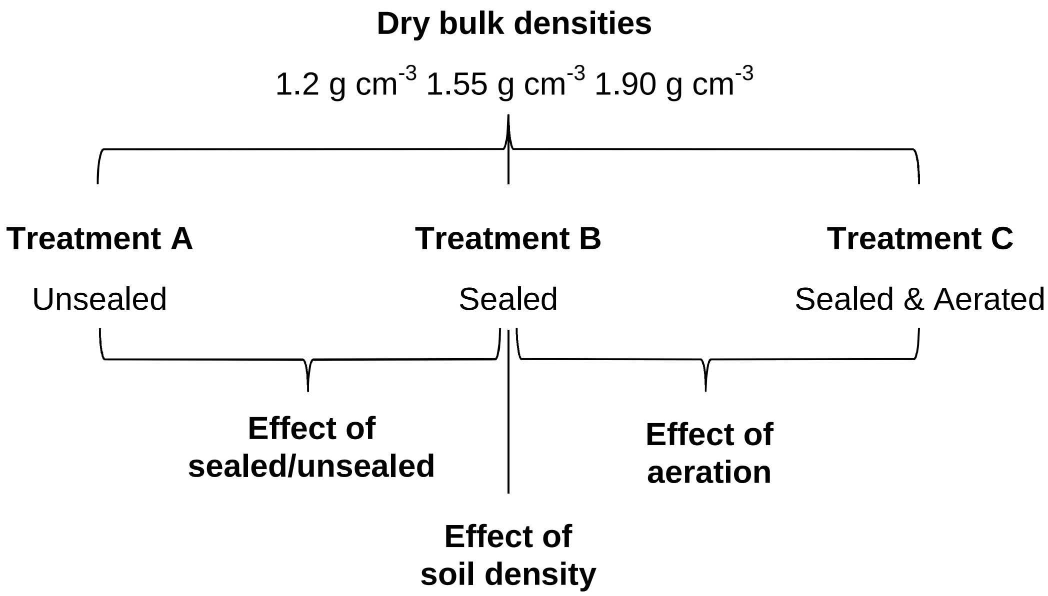


Figure 6.2 Flow diagram indicating experimental design.

In the unsealed units, treatment A, the base of the tube was covered by a nylon gauze to prevent the soil from escaping whilst allowing free movement of gases. The sealed treatments B and C had a PVC sheet (150 mm x 150 mm x 10 mm) bonded to the base, forming a complete seal. Each sealed unit was tested by filling the tube with water and assessing for leaks.

Each cylinder was filled with soil in three layers, each one 105 mm in thickness when fully compressed (Figure 6.3).

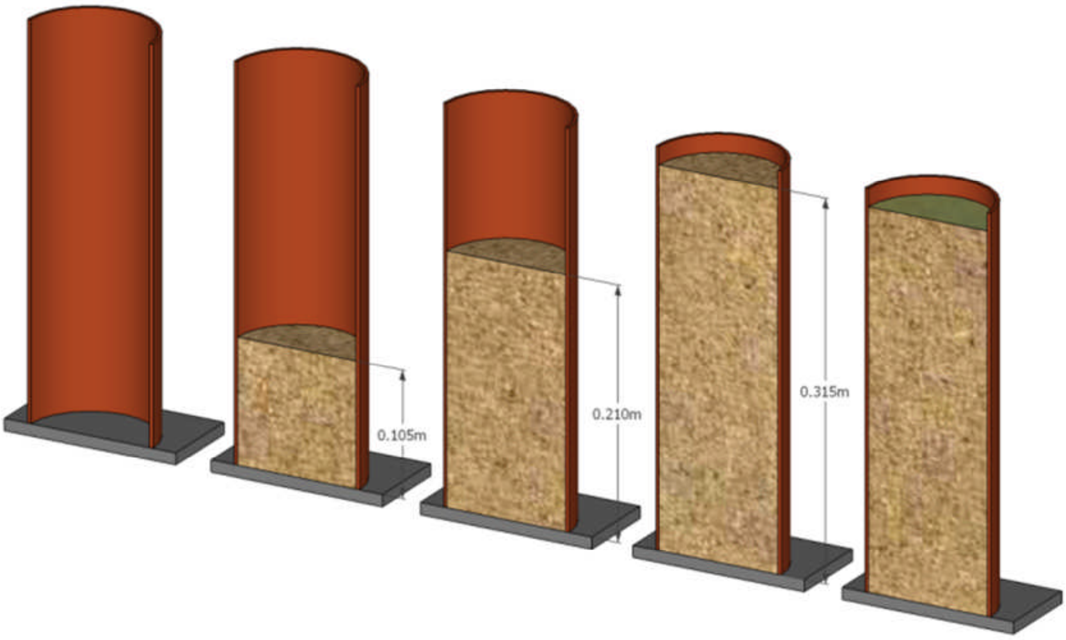


Figure 6.3 Cross section of the pots for Group B and C showing successive addition of layers.

The soil was packed in three layers each 105 mm in depth using an Avery E63215 (Avery Limited, Birmingham, UK) compression-tension machine to provide uniform packing consistency. The maximum loading capacity of the machine was 500 kN, of which 89 kN was required to achieve 1.90 g cm^{-3}. Each layer was keyed (the surface was scratched and aggravated using a sharp implement) to ensure each successive layer bound to the next. Table 6.1 gives the mass of soil required for each layer for a given density.

Table 6.1 Mass of dry soil required for each density required for each 105 mm packing layer

Density (g cm^{-3})	Mass of dry soil (g)
1.20	1197.42
1.55	1546.67
1.90	1995.70

The soil surface was keyed to provide a good seedbed. Each unit was seeded with a mixture of perennial ryegrass (*Lolium perenne*) varieties: 40% Sauvignon, 30% Evita and 30% Cassiopea. A sowing rate of 50 g m^{-2} was used with the addition of fertiliser (Pre-Seed fertiliser, Scotts, 8:12:8 N:P:K) at 25 g m^{-2}. The pots were placed in the glasshouse maintained at a minimum of 10 °C with 12 h of additional artificial light to stimulate growth from October 2010-1st February 2011. Simulated solid tine aeration to a depth of 75 mm was applied for treatment C on the 1st February 2011.

Grass was maintained at a height of 20 mm for the duration of the experiment except during growth trials.

Compaction may have indirect effects upon turfgrass growth due to nutrient and water deficiency if the roots are confined to a shallow layer of soil. Units were watered on an as and when needed basis regularly to try and minimise these factors (Matthieu *et al.*, 2011). No shrinkage of the soil away from the sides of the tube was observed.

6.2.1 Examination of dry leaf growth

In May 2011 grass clippings for each unit were collected for three periods, each lasting seven days. The clippings were oven dried at 105 °C for 24 h to record dry matter produced (±0.0001 g).

6.2.2 Dry root mass, root density and microbial biomass

In June 2011 the tubes were bisected and the soil core within removed. The soil core was then measured for total height and subdivided into six layers (Figure 6.4):

0-25 mm	125-175 mm
25-75 mm	175-250 mm
75-125 mm	250 mm –base of core

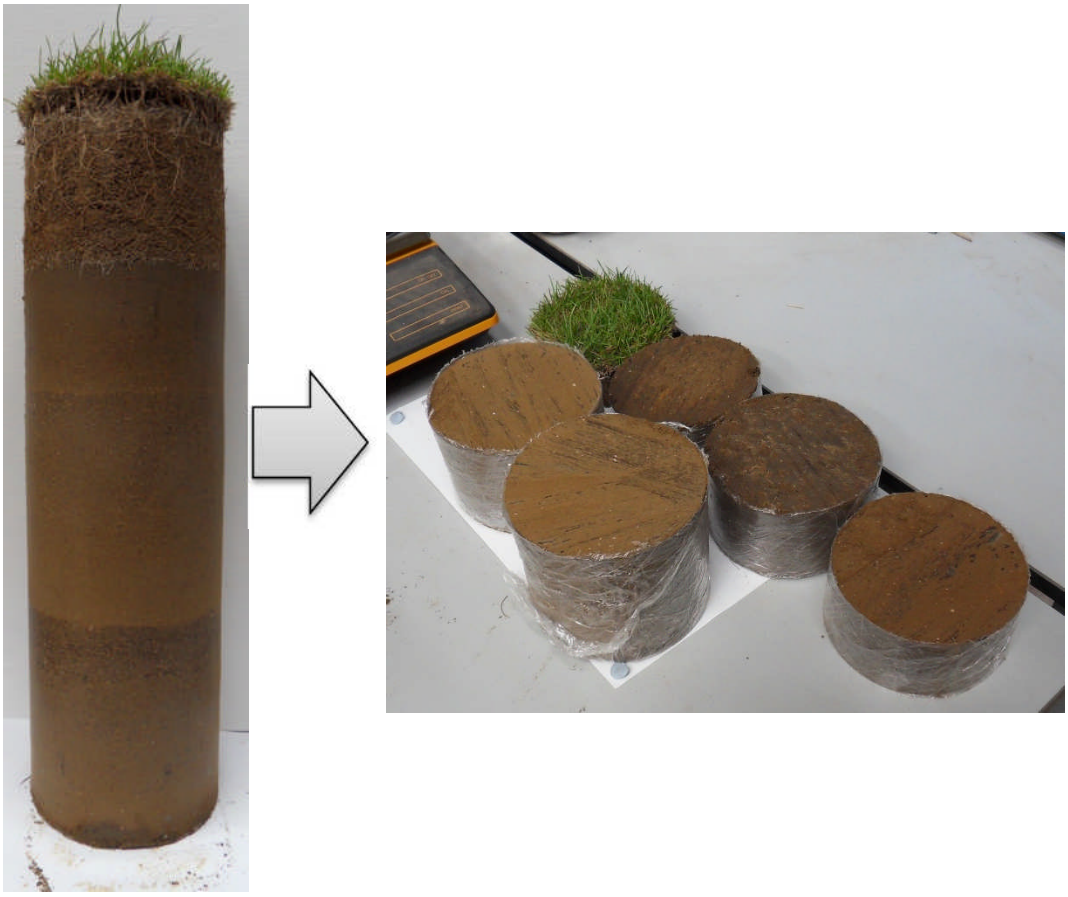


Figure 6.4 Photograph of an intact core (left) and of the same core subdivided into six layers (right).

Each layer was then subdivided into three sections by dividing the layer into two equal halves by cutting through the centre and then further subdividing one half into two quarters (Figure 6.5) using a template to ensure consistency. Two of the sections were measured for volume using dial callipers to ± 0.1 mm.

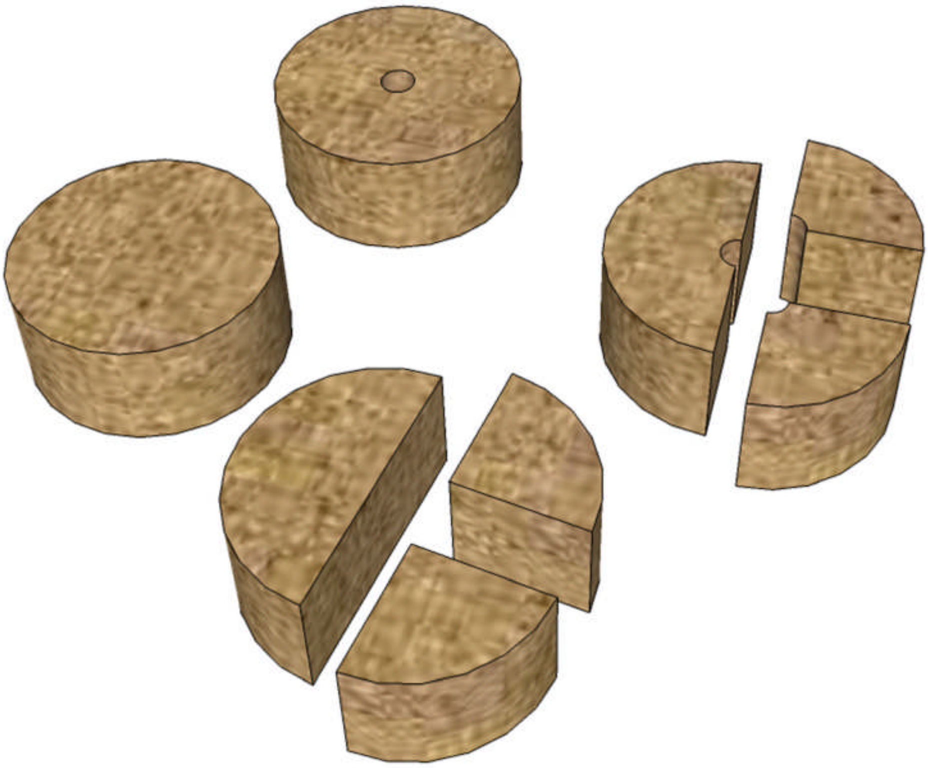


Figure 6.5 Illustration of two example layers, one aerated and one not, subdivided into three sections. Not the aeration hole is split between each section to ensure the effects were fully accounted for in the analysis of each section.

The first measured section was used to assess dry bulk density and moisture content. The sample was placed in a pre-weighed tin (±0.01 g), and the combined weight recorded (±0.01 g) before being dried at 105 °C for 24 h and reweighed.

The second section was used to determine dry root density. The samples were placed overnight on an end-to-end shaker with 150 ml of water and 50 ml buffered sodium hexametaphosphate dispersing solution (0.08 moles l^{-1} sodium hexametaphosphate, 0.07 moles l^{-1} anhydrous sodium carbonate). The resulting slurry was then washed over a 0.5 mm mesh sieve. The contents of the sieve were transferred to a bucket and the roots floated off onto a 0.1 mm mesh sieve. The contents of this sieve were then visually assessed and any non-root material removed. The remaining contents were transferred to a pre-weighed dish, dried at 105 °C for 24 h and reweighed.

The final section was used to determine microbial biomass. Samples were processed according to British Standard BS 7755: Section 4.4.2:1997 (British Standards Institution, 1997) (which is identical to ISO 14240-2:1997 (International Organisation for Standardisation, 1997)). Soil microbial biomass is the mass of intact microbial cells in a given sample estimated from the carbon content of these cells. Fumigation with chloroform causes the cells to lyse releasing the matter contained within. Non-living organic matter is not seriously affected by such fumigation. The organic carbon is extracted by 0.5 M potassium sulphate solution from fumigated and unfumigated samples and the increase used to calculate microbial biomass carbon.

Microbial biomass is a measure of the quantity of cytoplasm held within microbial cells so does not necessarily represent population directly. Microbial biomass is generally reduced by compaction. Compaction tends to increase the volume of smaller pores, which are the main living space for microorganisms (Table 6.2) so an increase would be expected on this basis.

Table 6.2 Neck diameters of accessible pores (Brussaard and van Faassen, 1994).

Group	Neck diameter of accessible pores (μm)
Nematode	>30
Protozoa	>5
Bacteria	>0.2
Not accessible	<0.2

However, secondary consequences of compaction dominate including reduced accessibility of organic substance for energy and nutrition and a restriction in gas exchange between the soil and atmosphere (Beylich *et al.*, 2010). Based on this information it is expected that microbial biomass will decrease with increasing density. Aeration should by facilitating gas exchange increase microbial biomass in the high density treatments in a manner similar to the root density.

6.3 Results & Discussion

As the layers of soil examined were of various sizes the results were weighted in the analysis to compensate for this.

6.3.1 Effect of restricted gas exchange

The growth rate of the grass as measured by dried cuttings per week was not significantly different between sealed and unsealed units.

The root density values showed a non-normal distribution.

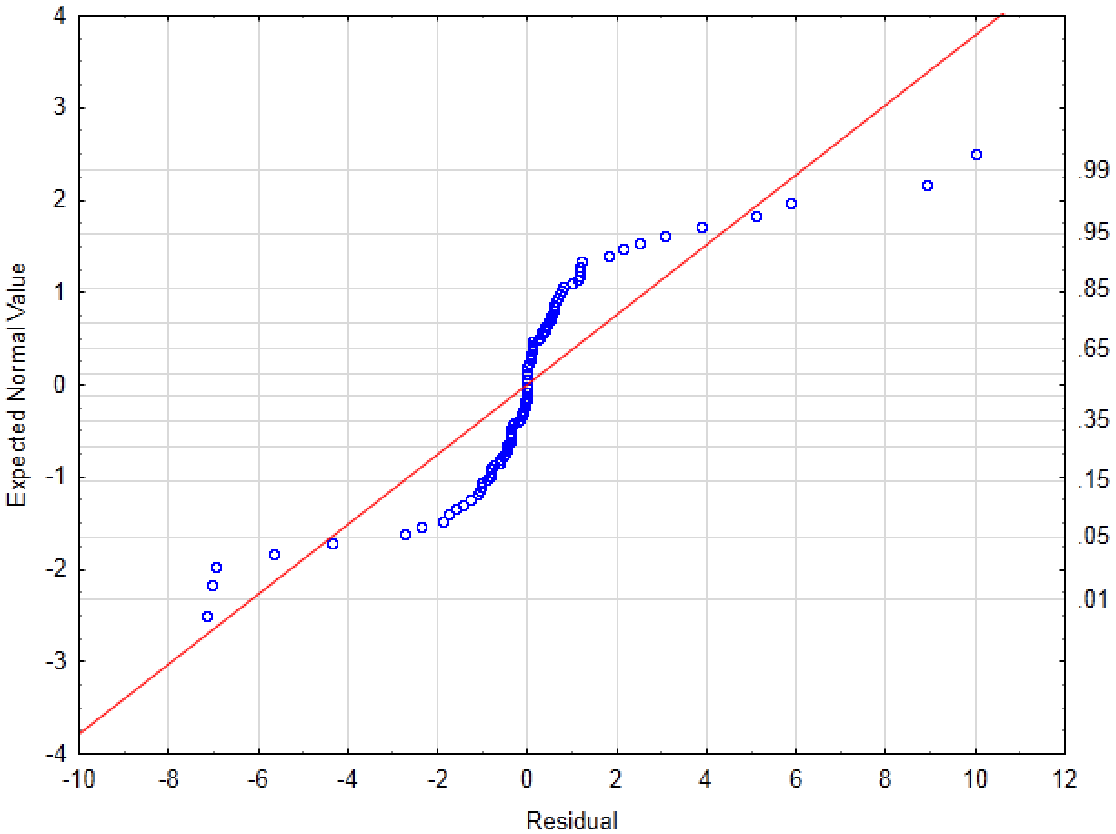


Figure 6.6 Normal probability plot of root density values showing a distinctive S-curve.

To analyse the results the natural logarithm of root density was used in its place which showed an acceptable normal distribution.

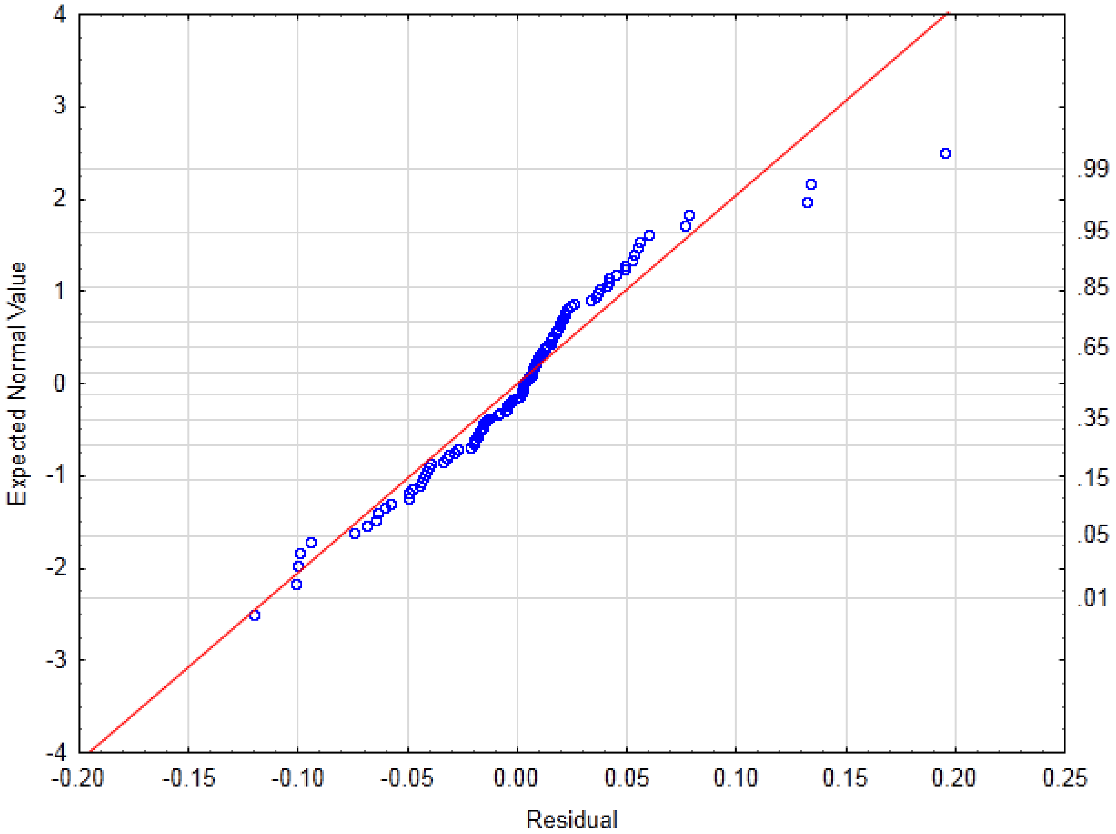


Figure 6.7 Normal probability plot of natural logarithm values of root density.

Root density was reduced in the unsealed units compared to the sealed units ($p<0.05$, Table 6.3).

Table 6.3 Mean total root mass and mean microbial biomass in sealed and unsealed units.

Treatment	Mean root density (kg m^{-3})		Microbial Biomass (µg C g^{-1})	
	Mean	Standard Error	Mean	Standard Error
Sealed	3.58	0.83	176.9	15.3
Unsealed	2.58	0.79	139.8	11.8

There was no depth interaction with sealed or unsealed treatment indicating that while overall root mass was different, the changes in root mass with depth were not affected by sealed or unsealed units. However there was an interaction of soil density and sealed and unsealed units affecting root density

(Figure 6.8). Generally the root density at each soil density was significantly different between sealed and unsealed units except at 1.90 g cm^{-3}.

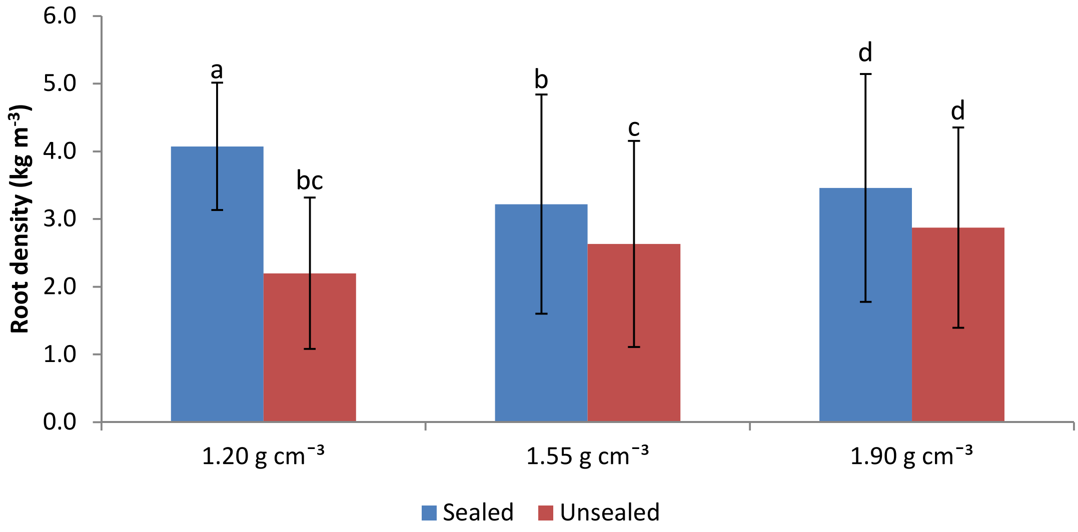


Figure 6.8 Mean over all depths of the root density for sealed and unsealed units (Treatments A and B) at each dry bulk density. Vertical bars denote standard error. Letter indicate homogenous groups at p<0.05.

Microbial biomass followed the same trend as root density (Figure 6.9) showing reduced levels in the unsealed units. Like root density there was a large reduction in value in the unsealed treatment relative to the sealed at 1.20 g cm^{-3} (Figure 6.9), however unlike root density microbial biomass was not significantly different between densities and between sealed and unsealed units for 1.55 g cm^{-3} and 1.90 g cm^{-3} apart from a slight rise in the unsealed 1.55 g cm^{-3} treatment.

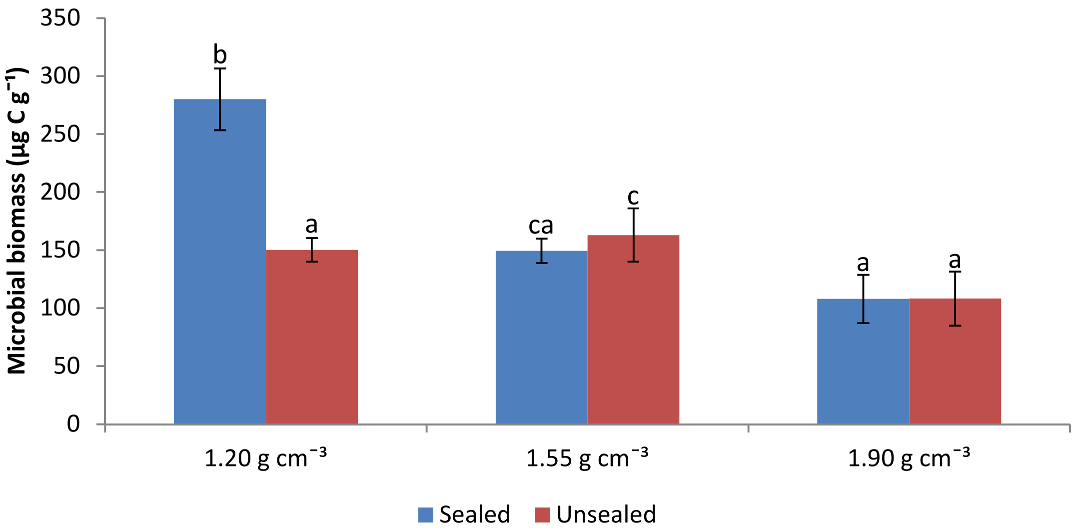


Figure 6.9 Mean over all depths of microbial biomass of sealed and unsealed units (Treatments A and B) for each density. Vertical bars denote standard error. Letter indicate homogenous groups at p<0.05.

The observed differences in microbial biomass and are also reflected in the moisture content of the units with treatment (Figure 6.10).

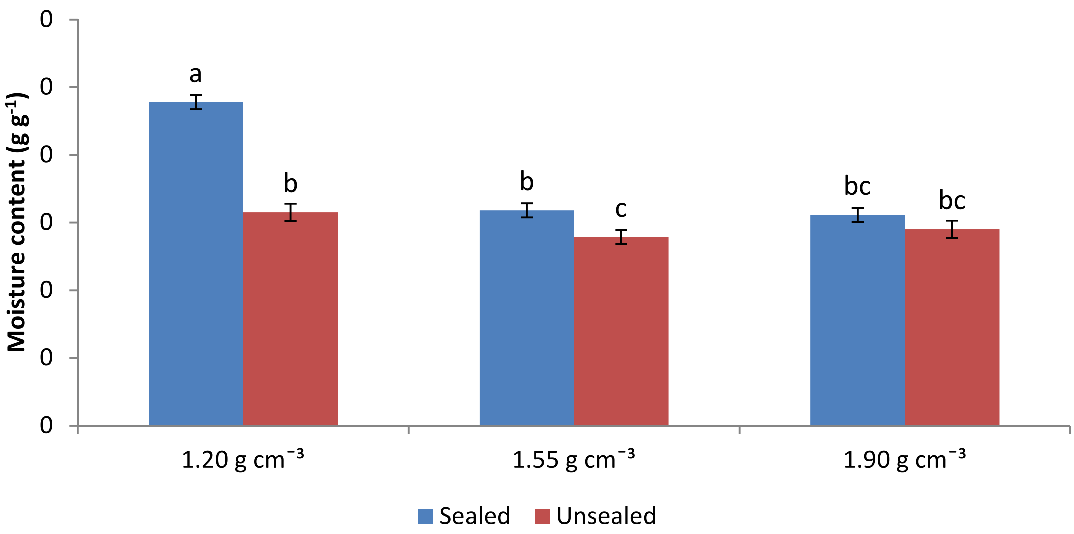


Figure 6.10 Mean gravimetric water content over all depths for sealed and unsealed units (Treatments A and B) for each density. Vertical bars denote standard error. Letter indicate homogenous groups at p<0.05.

An ANCOVA (analysis of covariance) analysis using moisture and measured soil density at each depth as continuous predictors and sealed or unsealed as categorical predictor revealed only depth, density and moisture as significant factors affecting both microbial biomass and root density. This does not imply that the sealed and unsealed treatment has no effect merely that the unsealed-sealed treatment affects moisture content, which in turn affects root density and microbial biomass.

6.3.2 Effect of density

The general effect of density was consistent regardless of aeration or sealed and unsealed units but for simplicity only sealed units (Treatments B and C) will be considered in the analysis of density and aeration effects.

6.3.2.1 Clipping Yield

The growth rate as measured by dry weight of clippings per week showed an inverse relationship with soil bulk density.

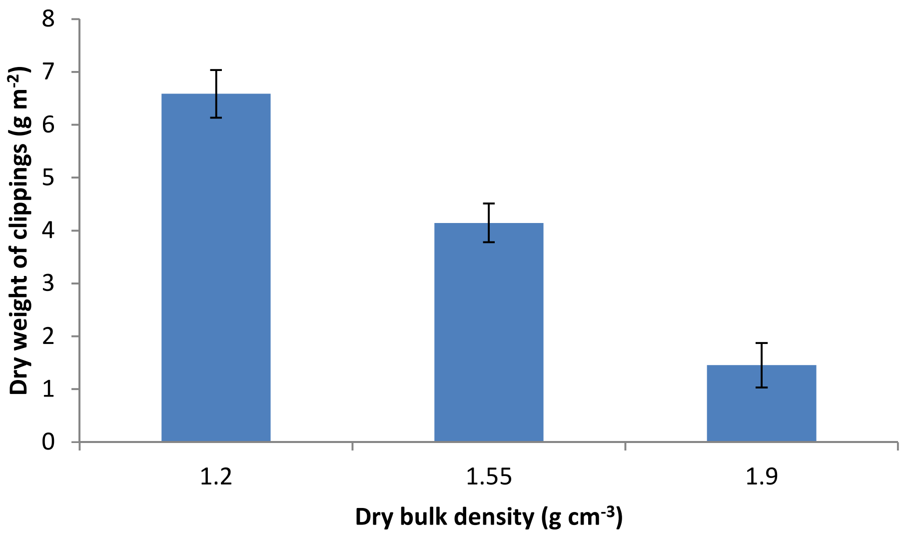


Figure 6.11 The effect of bulk density on the average growth rate of all units irrespective of treatment. Vertical bars denote standard error.

6.3.2.2 Root density

The root density was significantly different between all densities ($p<0.05$) but the differences were small, particularly between 1.55 g cm^{-3} and 1.90 g cm^{-3} (Table 6.4).

Table 6.4 Mean root density over all depths for each soil density.

Dry bulk density (g cm^{-3})	Root density (kg m^{-3})	
	Mean	Standard Error
1.20	3.95	0.75
1.55	3.46	1.25
1.90	3.49	1.19

The distribution of roots throughout the profile varies dramatically between densities (Figure 6.12). As soil density increases the root mass nearer the surface becomes greater but with a corresponding decrease at depth so that the overall root mass remains similar between densities.

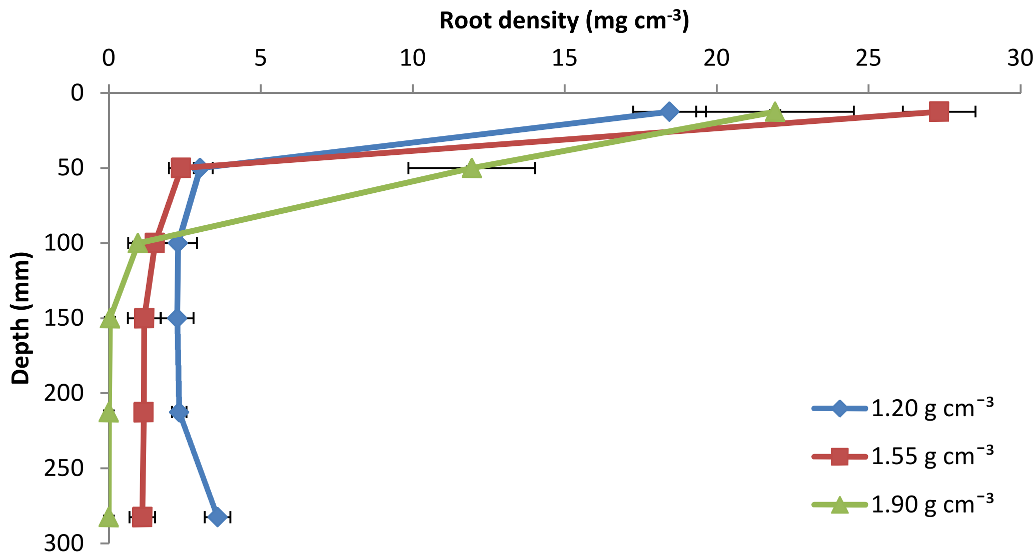


Figure 6.12 Root density through the profile of sealed units irrespective of aeration treatment

Table 6.5 Letters denoting homogenous groups at p<0.05 within-layers and within-soil density treatments for root density with depth in sealed units only for each density (Figure 6.12). Border formatting designates comparative groups.

Layer	Homogenous groups at p<0.05					
	Within-layer			Within density treatment		
	1.20 g cm^{-3}	1.55 g cm^{-3}	1.90 g cm^{-3}	1.20 g cm^{-3}	1.55 g cm^{-3}	1.90 g cm^{-3}
0-25 mm	a	a	a	a	a	a
25-75 mm	a	a	b	b	b	a
75-125 mm	a	a	b	b	b	b
125-175 mm	a	a	b	b	c	c
175-250 mm	a	b	c	b	c	c
250 mm - base	a	b	c	b	c	c

Figure 6.13 shows the calculated root mass distribution over a 315 mm profile, which more clearly shows how the distribution of roots throughout the profile changes and the relatively small difference there is in overall root mass between different soil density treatments.

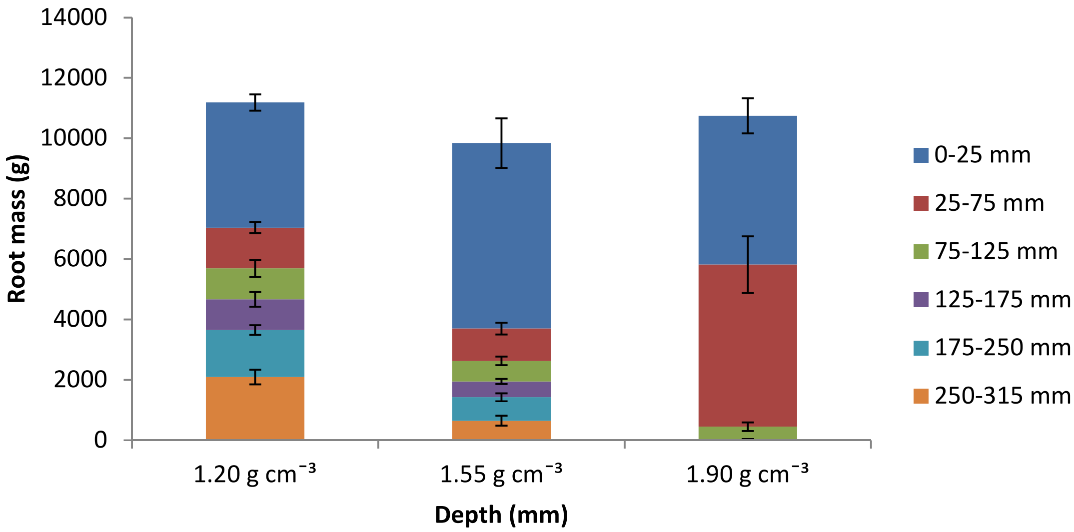


Figure 6.13 Dry mass of roots as calculated from root density values at each depth for each density irrespective of treatment. Vertical bars denote standard error.

6.3.2.3 Microbial Biomass

Significant effects were noted for depth, soil density and depth*soil density on soil microbial biomass. Soil microbial biomass drops precipitously between soil bulk densities of 1.20 g cm^{-3} and 1.55 g cm^{-3} then remains constant up to 1.90 g cm^{-3} as was observed for the sealed units in Figure 6.9. The same general trend of decreasing microbial biomass with density is visible within each layer though there is some variation in the top layer where the highest density soil shows the second highest microbial biomass between 0-25 mm and the greatest value between 25-75 mm before declining to a much lower value (Figure 6.14 and Table 6.6).

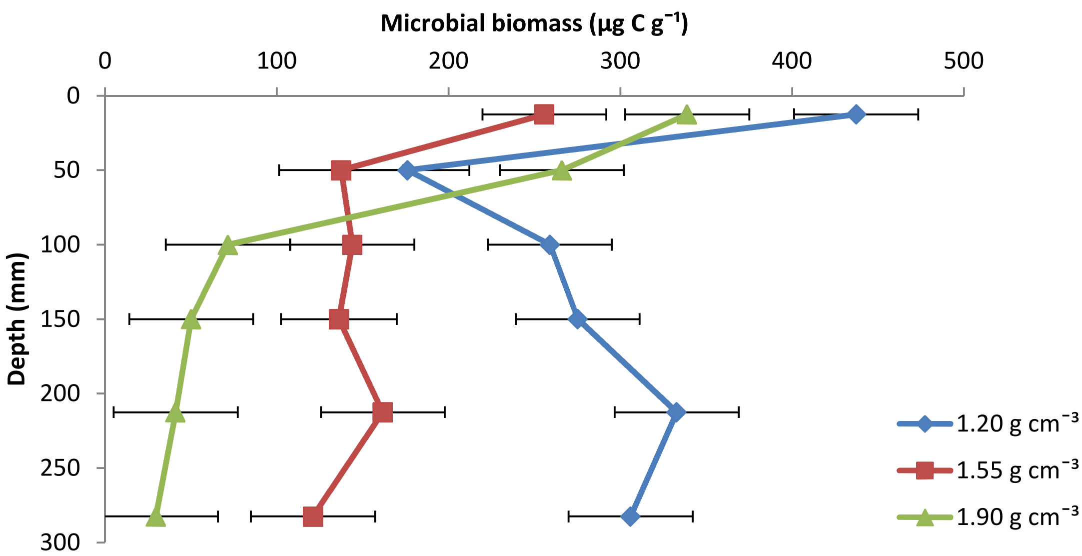


Figure 6.14 Microbial biomass with depth in sealed units only for each density. Horizontal bars denote standard error. Table 6.6 shows letters indicating within-layer homogenous groups at p<0.05.

Table 6.6 Letters denoting within layer homogenous groups at $p<0.05$ for microbial biomass with depth in sealed units only for each density (Figure 6.14). Border formatting designates comparative groups.

Homogenous groups within layers ($p<0.05$)			
Layer	Density		
	1.20 g cm^{-3}	1.55 g cm^{-3}	1.90 g cm^{-3}
0-25 mm	ac	b	c
25-75 mm	ac	a	c
75-125 mm	a	b	b
125-175 mm	a	b	b
175-250 mm	a	b	c
250-base mm	a	b	b

The distribution of microbial biomass with depth follows a similar trend to root density, though the relative magnitude of change between the values above 75 mm and below 75 mm is much smaller in microbial biomass than in root density.

6.3.2.4 Soil dry bulk density

The units were packed very carefully to ensure the density of the soil in each level was within ±0.02 g cm^{-3} of the target density. Over time the density of the units changed due to shrink-swell of the soil and the action of the roots so the density was non-uniform throughout the profile, the greatest changes occurring in the upper layers of the 1.90 g cm^{-3} units (Figure 6.15).

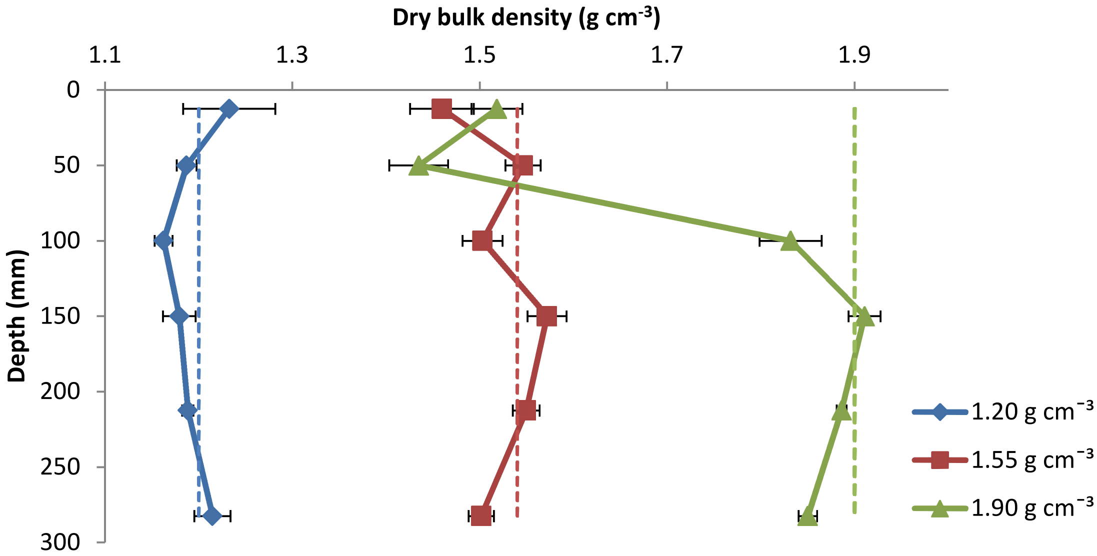


Figure 6.15 Mean dry bulk density at the end of the experiment within each layer for each initial soil density treatment. Horizontal bars denote standard error. Dashed lines indicate mean bulk density of units at start of experiment over all depths for Treatments B and C.

Examination of Figure 6.15 shows that the reduction in the 1.90 g cm^{-3} treatment chiefly occur above 75 mm depth with a much smaller reduction in the 75-125 mm layer. The reduction in density in this area is accompanied by a large value of root density. The general trend at each point in the profile below 75 mm is that the lowest bulk density has the greatest root density. Above 75 mm this relationship is broken down as:

> 0-25 mm the root density of each bulk density treatments were not significantly different.
>
> 25-75 mm the 1.90 g cm^{-3} units had the greatest root density; the 1.20 g cm^{-3} and 1.55 g cm^{-3} were not significantly different at this point.

The distribution of water is also non-uniform peaking at both the lowest and highest levels in the soil profile (Figure 6.16).

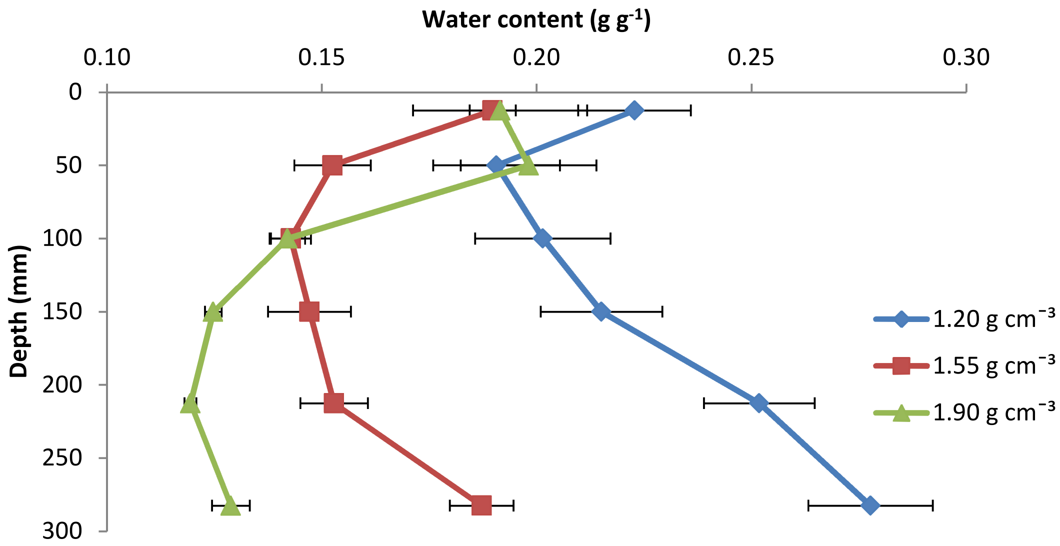


Figure 6.16 Mean water content at the end of the experiment within each layer for each initial soil density treatment. Horizontal bars denote standard error.

The distribution of roots in response to the changes in density and moisture were analysed using ANCOVA. Both moisture and density were significant factors, though the two are linked with moisture content becoming more variable as density decreases (Figure 6.17).

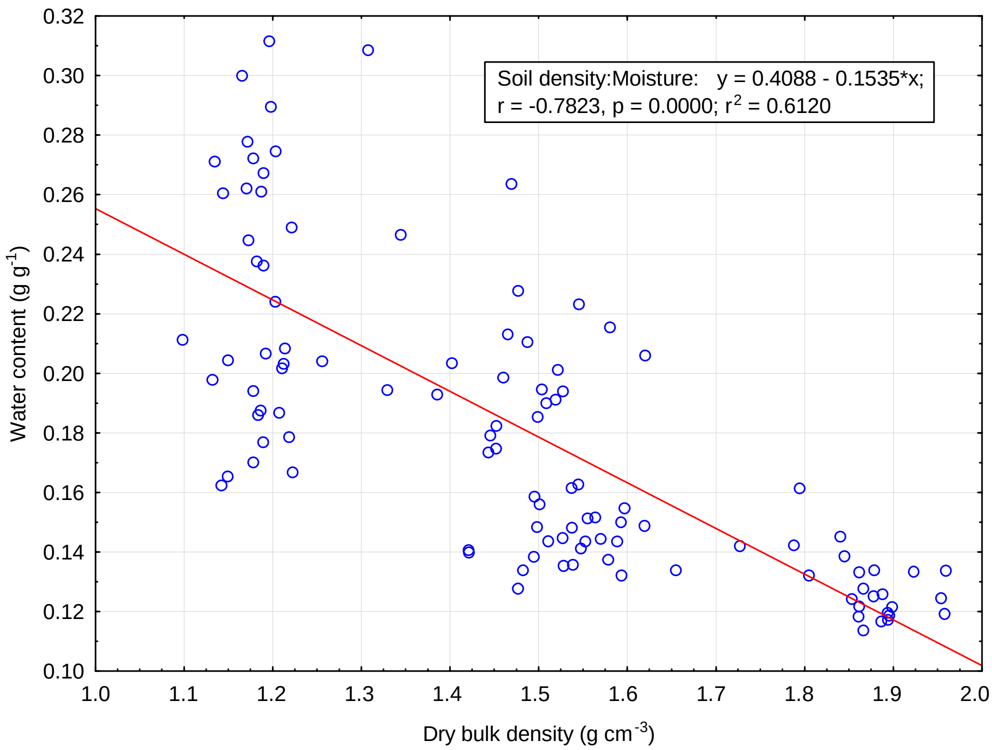


Figure 6.17 Regression of soil dry bulk density against gravimetric water content for all sealed units.

Moisture content is affected by both density and depth. The denser soils restrict infiltration and hydraulic conductivity which limits the water available lower down the profile. Also the sealed base prevents water from draining from the soil hence the second peak in water content at the base of the units, particularly in 1.20 g cm^{-3} as the water cannot leave the profile except by evapotranspiration. Inclusion of depth into the regression model improves the adjusted-r^2 marginally, and inclusion of root density raises it to 0.68. The addition of root density and depth does little to improve the model indicating an outside factor influencing moisture content possibly linked to infiltration of water in the soil in that the less dense soils were more able to absorb the water applied with less run-off than the high density soils. The 1.90 g cm^{-3} units would only absorb applied water very slowly the upper layers reaching saturation quickly but the water unable to penetrate further down the profile.

6.3.3 Effect of solid tine aeration

The only effect of aeration on root density occurred in 1.90 g cm^{-3} in the layer between 75-125 mm (Figure 6.18).

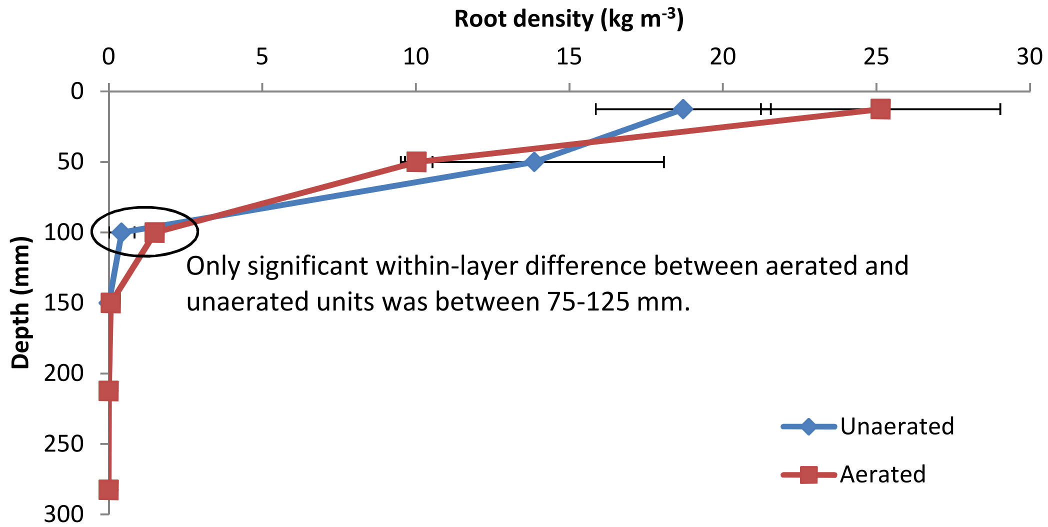


Figure 6.18 Comparison of the root density with depth in the aerated and unaerated treatments (Treatments B and C) at 1.90 g cm^{-3}. Horizontal bars denote standard error.

There were no detected effects of aeration on soil density, growth rate, microbial biomass, or soil water content.

6.4 Discussion

6.4.1 Sealed vs. Unsealed

When taking moisture content into consideration the effect of sealed or unsealed units is not significant. Moisture content is affected by sealed or unsealed treatment which in turn affects root density. Figure 6.10 showed that in 1.20 g cm^{-3} there was a large difference in moisture content between the sealed and unsealed units which corresponds to the large difference seen in the same density soil in microbial biomass and root density. There was a slight difference in moisture content between the 1.55 g cm^{-3} sealed and unsealed units which showed a corresponding smaller difference in root density. The similarity of the sealed and unsealed values at densities above 1.20 g cm^{-3} indicate that the soil at depth acts in a way similar to sealing the base of the unit by preventing the water from draining straight through the base of the core without being absorbed. This can be seen in the water distributions at each density over the profile in the sealed and unsealed units (Figure 6.19) where the water content in 1.20 g cm^{-3} units is substantially different between sealed and unsealed units and the remaining two densities with much smaller differences between sealed and unsealed units. Water content is likely to change more rapidly than root density over time and while there is only one measurement of each, the data available would indicate that the difference in values of microbial biomass and root density between the sealed and unsealed units at 1.20 g cm^{-3} is due to restrictions on the availability of water in the sealed unit relative to the unsealed rather than restrictions on gas exchange where it would be expected that the sealed units would show reduced root density compared to the unsealed units.

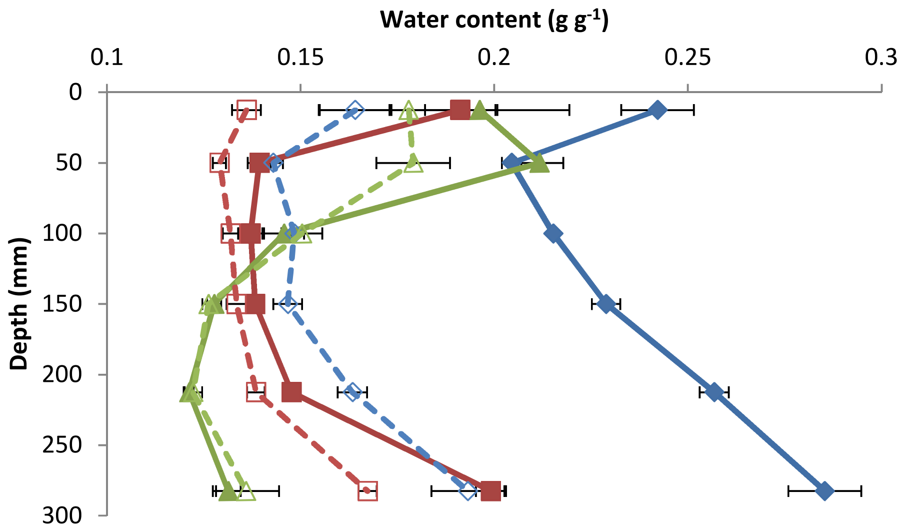


Figure 6.19 The water content at each measured point in the soil profile at each density. Open symbols and dashed lines show unsealed units, closed symbols and solid lines show sealed values. ♦ indicates 1.20 g cm^{-3} units, ■ indicates 1.55 g cm^{-3} units, ▲ indicates 1.90 g cm^{-3} units. Horizantal lines indicate standard error.

6.4.2 Density

The growth rate of the grass was reduced as density increased in agreement with the findings of Cook *et al.* (1996) and Carrow (1980). Total root density also showed an inverse relationship with density. The greatest reduction in root density was between 1.20 g cm^{-3} and 1.55 g cm^{-3} with a much smaller reduction between 1.55 g cm^{-3} and 1.90 g cm^{-3}. The reduction in shoot growth follows an almost linear relationship over the densities measured whereas the root density follows a law of diminishing returns with each unit increase in density corresponding to a smaller decrease in root density. Sills and Carrow (1983) found decreasing root density in perennial ryegrass in a silt loam with increasing dry bulk density. The difference between the root densities were much smaller than the comparative changes in shoot growth possibly explaining the null result found by Shipton (2008) and Matthieu *et al.* (2011) as total root density appears to be a lot less sensitive to bulk density than shoot growth.

Most striking is the change induced by bulk density on the distribution of roots through the profile. Density causes the roots to concentrate upwards through the profile and is widely reported (Shipton, 2008; Matthieu *et al.*, 2011; Carrow, 1980). Lynch (2007) asserts that roots near the surface are for nutrient acquisition and that deeper roots are for water uptake. As these units were watered regularly and fertilised this could disrupt the natural behaviour of the root system. The added water did not penetrate deeply into the 1.9 g cm^{-3} unit and tended to concentrate nearer the surface so the most effective distribution of the root system would be to accumulate in this area.

The dry bulk density of the units changed throughout the trial period, particularly in the 1.90 g cm^{-3} units where the mean bulk density was significantly reduced (Table 6.7).

Table 6.7 Dry bulk density of units in Treatment B and C at the start and end of the experiment for each target density treatment.

Dry bulk density (g cm^{-3})		
Target	Start	Finish
1.2	1.2	1.19
1.55	1.54	1.52
1.9	1.9	1.74

The reduction in bulk density was not uniform and was concentrated in the top 75 mm of the profile accompanied by a large increase in root density. Observations of the 1.90 g cm^{-3} cores revealed a clear contrast between the root-penetrated soil and root-free soil (Figure 6.20). The root-penetrated layer was soft and springy relative to the intensely hard dense soil beneath which was unyielding to the touch. Upon initial watering of the units the 1.90 g cm^{-3} cores swelled noticeably, increasing in height by approximately 15 mm, indicating significant shrink-swell. Dexter (1991) found that cracks produced by shrink-swell of soil through wetting and drying cycles particularly if the soil is wetted rapidly (as is the case here) cracks in the soil will form both from drying and air-slaking (Section 4) breaking down the compaction within the soil and providing routes of reduced mechanical impedance for root growth which help stabilise the new structure.

Figure 6.20 Photograph of the upper third of a typical 1.90 g cm^{-3} soil core (left) showing contrast of root-penetrated and root-free soil together with a magnified section of the border (right). The layer of root penetrated soil was present throughout the soil profile to the same general depth indicating it was not an edge effect, unfortunately no sectioned photos were taken to illustrate this.

Based on this it would seem that the bulk density of 1.90 g cm^{-3} does form a mechanical barrier to root penetration and requires the action of water to break down the soil compaction. Matthieu *et al.* (2011) stated that if the overall root biomass is the same then distribution differences are due to compaction. The lower densities both showed diminishing root density with depth but crucially root growth was not prevented at depth as roots had penetrated to the base of all the units. In 1.2 g cm^{-3} there was a slight rise in root density at the lowest depth to aid water uptake as the soil was relatively free draining such that when water was added it would pass to the bottom of the unit before being absorbed by the soil which is reflected in the moisture content data (Figure 6.16).

The microbial biomass follows the same general trend as root density. This is not entirely surprising as the grass plants represent the main source of nutritional input for microbes in this soil (Bartlett *et al.*, 2008; Zvyagintev, 1994). The microbial biomass is not zero in soil containing no roots indicating an underlying microbial activity independent of root activity as was seen in Section 5. The microbial biomass shows a distinct reduction in value at the base of the 1.20 g cm^{-3} and 1.55 g cm^{-3} units. There is a distinct rise in moisture content at the base, together with the reduction in microbial biomass which could indicate instances of high water content creating hypoxic conditions.

6.4.3 Effect of solid tine aeration

The influence of solid tine aeration on the properties measured was minimal. Only in the greatest density units was a single aeration effect significant. The effect of aeration in the 1.90 g cm^{-3} units was to slightly raise the root density in the 75-125 mm layer. There were no detectable effects of aeration on the density or moisture, nor was there a significant increase in the depth of root penetration in the 1.90 g cm^{-3} units. Within the tine hole it was noted that often there was a mat of roots at the base which could account for the increase in root density (Figure 6.21). Whether this mass of roots develops because the tine hole represents a reservoir of easily accessible water or because it presents as a route of low mechanical impedance cannot be determined.

Figure 6.21 View of the base of the 25-75 mm layer of an aerated 1.90 g cm^{-3} unit showing the mass of roots growing in the base of the tine hole.

The lack of detectable effect on bulk density and moisture content can be interpreted in two ways. Either aeration is ineffective at producing a noticeable change or natural processes within the soil are much more effective and any changes due to aeration are undetectable in comparison. This could explain the apparent effectiveness of aeration in sand dominated golf courses (Rieke and Murphy, 1989) and the apparent lack of definitive action in clay-based soils as the sandy soils lack the shrink-swell capacity to self-ameliorate. In light of this it is possible that had the aeration treatment been applied to a greater depth beyond that which the natural processes of self-amelioration had reached then a noticeable aeration effects may have been recorded as soil at greater depth gains greater exposure to water and air, facilitating shrink-swell cycles via the aeration macropore.

6.4.4 Method limitations and suggestions for future work

Factors affecting root growth in soil are many and varied. Attempting to control them all is extremely difficult particularly water content in a non-draining, sealed unit. As the density increases the volume for water content decreases as pore space decreases. In order to reduce the influence of moisture content on root growth it would be better to maintain the soil units at a constant level of water availability to the plant, i.e. a tension equal for all cores. However, in terms of maintaining a cricket pitch a highly compacted layer will influence moisture content in the soil above and below which cannot be avoided so ideally a comparison of constant tension and natural water content should be used to separate the effects of moisture and density on root growth. This could be achieved by repeating the experiment with some units based permanently on a tension table to maintain constant water content in the profile.

It was noticed in the 1.90 g cm^{-3} units that the profile was visibly altered by the effect of shrink-swell and root penetration. Had this visual information been available a more informative depth of aeration treatment may have been applied so that the depth of aeration exceeded the natural state, though this is mere conjecture that the limit reached naturally would have been extended if aeration penetrated beyond it. It is suggested that an experiment involving time-lapse photography to monitor the extent of the changes in bare soil and grassed units and secondly how they interact with aeration so as to separate the action of roots and shrink-swell in soil amelioration. Ideally X-ray computed tomography would be used to assess this to gain a full three dimensional view of the process, but in lieu of this expensive technique a glass sided chamber and a normal camera would suffice.

Rarely is a totally uniform profile encountered and more likely there will be areas of compacted soils interspaced with less compacted areas. In an artificially compacted profile like a heavily rolled cricket pitch there would still be variation vertically in the profile if not laterally. Murphy *et al.* (1993) cited the possible development of a hard pan in the soil from repeated aeration treatments to the same or similar depths. Rolling will create a compacted layer on or near the surface. The root growth response in uniform profiles is different to those of layered profiles (Matthieu *et al.*, 2011; Shipton, 2008). In a profile with a sub-surface compacted layer if it is aerated so that the tine holes pass through the compacted layer into the soil beneath this could have a markedly different effect than aeration into a uniform profile.

Root breaks in cricket pitches due to non-binding layers of soil and improper rolling (Section 1) have been reported as a barrier to deeper root growth as the roots grow laterally along the path of least resistance rather than vertically across the break. A further test similar to that suggested for a sub-surface compacted layer could be investigated replacing the compacted layer with a root break.

Finally, the units were created from industrially prepared soil potentially lacking the soil structure that would have developed with time or that which is present in the field. Hence field trials assessing the implications of aeration on root growth are suggested and were examined in Section 7.

6.5 Conclusions and relevance to cricket

The desire for deep rooting and high bulk density cricket pitches seem mutually exclusive from the evidence presented here as increasing soil bulk density causes root growth to become increasingly concentrated upwards in the profile. Increasing root mass at the surface presents two problems for Groundsmen. Firstly, a shallow root system leaves the grass plant more vulnerable to drought and nutrient shortages unless these are supplemented in the upkeep of the pitch (Beylich *et al.*, 2010). While this is easily negated by Groundsmen with the resources and time to irrigate regularly and apply fertiliser to keep the plant adequately supplied, those with few resources particularly access to water and time for regular irrigation, could find this very detrimental to the health of the plant and consequently the pitch as a whole.

The second and less easily solved problem is that the total mass of roots was only very slightly reduced by density, meaning that the same mass of roots that was spread over a greater distance in the profile is now concentrated in the upper horizons. Coupled with the reduction in microbial biomass as a consequence of compaction this root-concentrated layer will very quickly build-up organic matter. Pitches high in organic matter tend to be soft, slow and unpredictable as the organic matter acts like a spring and resists compaction. Organic matter build up has been highlighted as a problem facing many pitches (Bartlett *et al.*, 2009) and recommendations suggest having no more than 7% organic matter content (ECB Staff, 2007). In the upper horizons of the soil the lack of overburden means shrink-swell processes are more effective and oxygen supply is not likely to be a limiting factor, with this in mind traditional aeration practices using solid tines are unlikely to have an effect in reducing the organic matter build up. On golf courses, organic matter build up has been subject to much research and generally accepted practice is to physically remove and replace the soil by hollow tining and back filling to reduce organic matter. Hollow tining is not suitable for cricket pitches as it tends to disrupt the surface and the plugs of soil get stuck in the tines rendering it ineffective (Woods, 2012). The Deep Drill would be an alternative soil removal technique but unless the pitch is treated repeatedly and regularly the amount of organic matter removed is likely to be small compared to overall production (Section 7). Linear aeration in this case may prove the most successful in removing this build-up but typically this is not applied deeper than 20 mm leaving 50 mm of potential root build-up untouched. An alternative strategy is that used in New Zealand which is to fraise mow the top 20-30 mm of soil from the pitch and leave it bare over winter and then rebuild and reseed in the spring. This approach is designed specifically to reduce deep rooting so as to prevent a build-up of organic matter leaving it primarily in the layer that is removed each year (Carter, 2012).

In a more structured soil these affects may not be observed. In cricket pitches exposed to the elements natural shrink-swell and air slaking processes should break down compaction and allow root penetration. Repeated annual rolling may however render these processes ineffective particularly near the surface. Biopores left by dead roots and earthworm tunnels provide a secondary natural process of soil amelioration enabling root penetration. Dexter (1991) found that these natural processes of soil amelioration tended to be more effective than tillage in agricultural systems. In the context of a cricket pitch where tillage operations are limited by the amount of surface disruption it would seem that natural processes would be of even greater importance. It may be more important to consider why compaction problems are not being broken down by natural processes rather than trying to find artificial cures.

Aeration marginally increased root density in the highest bulk density soil and the increase appeared to come primarily from root growth inside the artificial macropores created. This root growth is of little value in terms of pitch improvement as it will not aid consistent removal of moisture from the soil (as it is not spread through the soil matrix) nor is it increasing soil strength to prevent crack formation, it simply represents a build-up of organic matter. This is in a uniformly high bulk density soil however. Potentially if there was a compact layer through which the tine hole penetrated into less compacted soil below, the macropore created would act as a conduit through the compacted layer. As the solid tines are known to cause compaction around the tine hole however this may be ineffective as a treatment as the walls of the tine hole may be sufficiently hard to restrict growth. Techniques such as the drilling which scrape away and remove the soil rather than displacing and compressing may be more effective for this purpose as the walls of the pore should be less resistant to root penetration.

In order to reach a definitive conclusion on the effectiveness of aeration a greater range of soil profile scenarios must be tested, including subsurface compaction and the effectiveness of aeration in providing conduits through them. In non-layered soil profiles aeration does not increase deep rooting and seemingly only marginally effects root density at the extreme end of the bulk densities tested. Aeration did not produce a noticeable change in microbial biomass, bulk density or moisture content so unless there is layering in the profile aeration seems to be without purpose in these systems.

7 Field Trials of Equipment

7.1 Introduction

Laboratory and pot experiments examining the effects of aeration and soil mechanical properties provide the basis for understanding the processes involved. The experiments however cannot accurately represent the conditions found in the field on a real cricket pitch. To transfer the knowledge gained from the laboratory and pot experiments into the field, a series of experiments were designed to examine the effect of aeration on soil physical and biological properties on field plots mimicking the conditions of a real cricket pitch.

Field trials spanned a total of 28 months with aeration treatments applied annually or biennially in line with common practice. Crucial to the effectiveness of aeration are the soil conditions at the time of treatment application, particularly moisture content, and the effect of over-winter bulk density changes from frost-heave and shrink-swell processes in the soil.

7.1.1 Experimental Approach

Five different aeration treatments were applied to a test area constructed to mimic cricket pitches at Cranfield University, Silsoe. The treatments used include solid tining, air and water injection, linear aeration and soil drilling techniques.

Three sets of field trial experiments are detailed here:

Experiment one (Section 7.2) examines the immediate effects of aeration treatments on the physical properties of the soil over three years of repeated treatments. The area was assessed using penetration resistance and surface rebound hardness.

Experiment two (Section 7.3) examines the same treatments every four months from October 2008 to February 2011. Each treatment was assessed for changes in soil physical properties using dry bulk density, soil water content, penetration resistance, and surface hardness. Microbial biomass and organic matter contents were used to assess the effect of aeration on soil biology.

Finally in April 2011 (Section 7.4), six trenches were dug across the treatment area to provide qualitative visual assessment of aeration treatments on the soil. At the same time quantitative analysis of infiltration rate and dry weight of roots at four depths were undertaken for each treatment.

The test area was constructed for use in the rolling trials in Shipton (2008). Two soil types were used in the construction of the pitches. The soils were selected as a representative sample of soils used in the construction of modern cricket pitches in the UK in a first class facility (Soil O) and at a lower club or school level (Soil K) (Table 7.1)

Table 7.1 Soil particle size distribution and textural class for the two trial site soils. Data from Shipton (2008).

Particle size		Soil O	Soil K
Coarse sand	0.6mm - 2mm (%)	4.6	4.1
Medium sand	0.212mm - 0.6mm (%)	14.7	26.9
Fine sand	0.063mm - 0.212mm (%)	10.5	16.2
Total sand	**2mm - 0.063mm (%)**	29.8	47.2
Silt	**0.002mm - 0.063mm (%)**	39.8	27.3
Clay	**<0.002mm (%)**	30.4	25.5
UK textural classification		Clay loam	Clay loam

The trial area measures 13 m length by 8 m width. The area was split equally lengthways and widthways to create four quadrants each 6.5 m by 4 m, two constructed using Soil K and two constructed using Soil O. Seven trial plots were used each stretching the length of the test area, 13 m, covering an equal area of Soil K and Soil O (Figure 7.1).

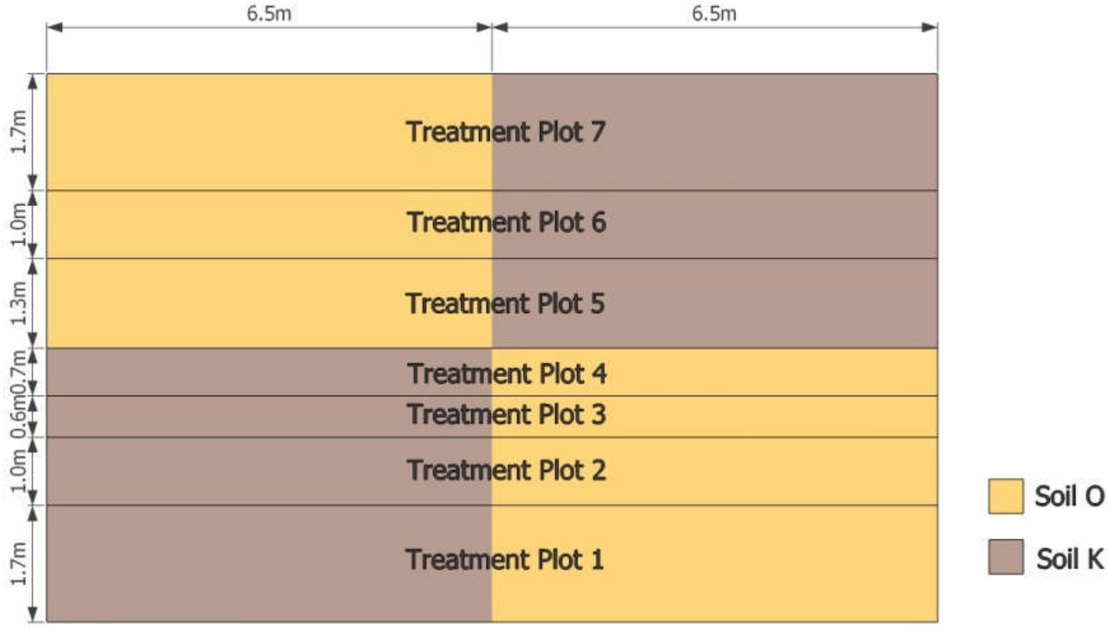


Figure 7.1 Layout of trial plots in test area

The soil profile consists of 200 mm of clay loam over 50 mm of sharp sand on top of natural soil. Five of the seven plots were treated with aeration equipment; two plots were left as controls (Table 7.2).

Table 7.2 Timing and frequency of treatments together with plot assignments

Treatment Plot	Treatment	2008		2009		2010	
		Nov	Dec	Nov	Dec	Nov	Dec
1	Air Injection	✓	✓	✓	✓	✓	✓
2	Spiked roller	✓					
2	Linear aerator			✓		✓	
3	Solid tine	✓	✓	✓	✓	✓	✓
4	Control						
5	Control						
6	Deep Drill	✓		✓		✓	
7	Water injection	✓	✓	✓	✓		

A description of the action of the five aeration treatments used:

Solid tine – A solid metal tine (7 mm diameter, 127 mm length) driven vertically into the soil to a depth of 90 mm. Tine spacing was 50 mm in a square packing arrangement. The machine was a motorised, pedestrian version.

Solid tine with air injection – A metal tine (10 mm diameter, 127 mm length) driven vertically into the soil to a depth of 90 mm. Tine spacing was 80 mm by 25 mm. At maximum penetration into the soil compressed air is blasted from a side hole in the tine approximately 15 mm from tip at a pressure of 300 kPa. The machine was tractor mounted and PTO driven.

Spiked roller – Consists of a barrel coated in parallel lines of spikes (5mm diameter, 30 mm length). Tine hole spacing was 30 mm in a square packing arrangement. Machine was a motorised pedestrian version.

Linear aeration – A series of fast spinning blades that slice 20 mm into the soil. Blade width (4 mm), blade spacing (35 mm). This was a tractor mounted unit.

Deep drill – A total of 60 ‘auger’ drill bits (10 mm diameter, 250 mm length) arranged in a square pattern (spacing 110 mm). The unit drills into the soil to an operating depth of 250 mm, ejecting soil onto the surface. The soil surface was brushed to remove debris post treatment. This is a specialist vehicle, approximately the size of a small tractor, powered by a 21 hp engine with a ground pressure of approximately 62 kPa.

Water injection – Water is injected into the soil by high powered jets of water at a working pressure of 34 MPa. This is a motorised pedestrian unit.

Air injection, solid tining and spiked roller treatments were repeated in December each year (Spiked Roller only used in 2008) to mimic common practice (Section 3). The December treatments of these machines when examining the immediate effects will be referred to as Air Injection 2, Solid Tine 2 and Spiked Roller 2.

Each trial plot was subdivided into ten equal sections 1.3 m in length along the long axis. This resulted in five subplots per soil per aeration treatment (Figure 7.2).

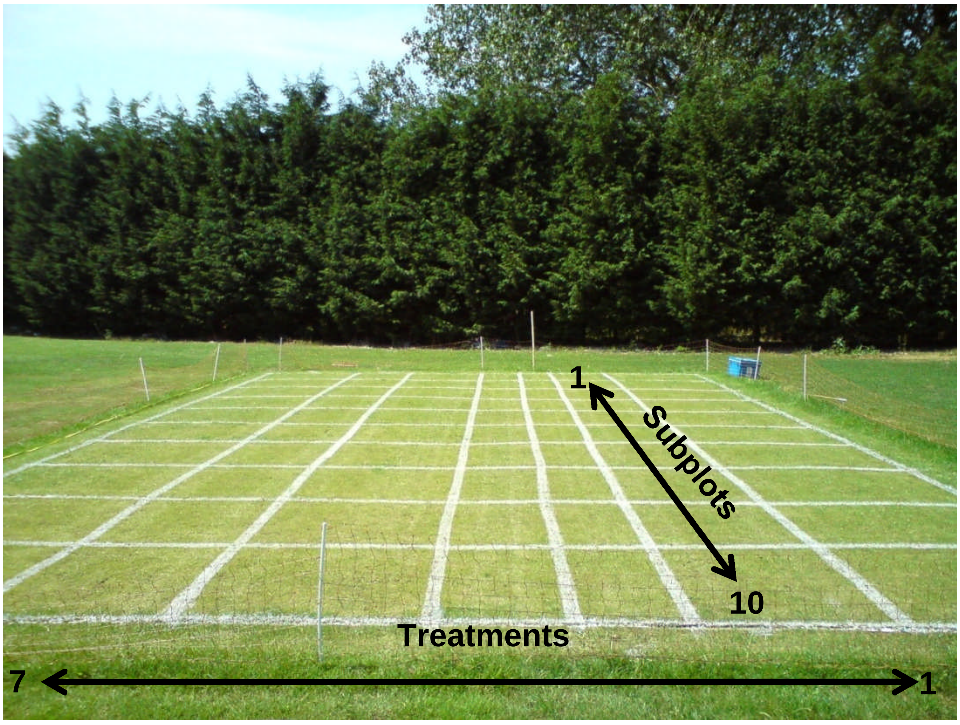


Figure 7.2 Photograph of experimental area showing seven vertical treatment strips subdivided along the horizontal axis to give ten sampling subplots.

7.1.2 Surface hardness and penetration resistance in relation to soil water content and dry bulk density

In both Experiment One and Experiment Two the surface hardness (SH) and penetration resistance of the soil were measured. These methods of measurement are highly correlated with soil bulk density and soil moisture content both of which must be carefully considered when analysing the data. The relationships between moisture content and bulk density with penetration resistance and SH are discussed here as they are relevant in both Section 7.3 and Section 7.2.

SH was determined using a 0.5 kg Clegg Impact Soil Tester. The device consists of a 0.5 kg missile fitted with an accelerometer dropped from a height of 0.55 m three times in the same position. The device measures the peak deceleration of the missile on impact with the surface which is directly related to the stiffness and shear resistance of the soil (Clegg, 1980); the greater the peak deceleration the harder the surface. The data from the third drop was used as recommended by the manufacturer.

Soil penetration resistance was measured using an Eijkelkamp Penetrologger with a 30°, 130 mm^2 base area cone at a speed of 30 mm s^{-1} measured every 10 mm to a depth of 150 mm. The properties measured using this device were the energy required to penetrate the ground to 150 mm (ERP) and the depth of maximum resistance (DMR) and magnitude of the maximum resistance of the soil to penetration (MRP). ERP was calculated from the area under the curve formed by plotting the recorded pressure against distance and multiplying by the area of the cone. The points were assumed to be connected by straight-lines and the area calculated by the sum of a series of trapeziums formed from two adjacent points and the base line.

Both SH and penetration resistance were shown by Shipton (2008) to be highly dependent upon moisture content and dry bulk density.

Multiple regression analysis in Statistica 10 (Statsoft, USA) using moisture content and dry bulk density as explanatory variables produced a significant model for the prediction of SH (Table 7.3). The results were independent of soil type and organic matter content.

Table 7.3 Multiple regression model for surface hardness (Gravities). Explanatory variables are dry bulk density and gravimetric moisture content. b* is the standardised regression coefficient. Contribution uses b* to calculate the relative importance of each variable to the model.

Explanatory variables	b^*	Regression coefficient	Contribution	p-value
Intercept		1551		<0.001
Moisture	-0.93	-2872	75%	<0.001
Density	-0.30	-463	25%	<0.001
Summary statistics				
Multiple R		0.812		
Multiple R^2		0.659		
Adjusted R^2		0.657		
$F(2,322)$		311.57		
p		<0.001		
Standard error of estimate		119.94		

This is similar to the model reported by Shipton (2008) who found over the same test area and soils that the contribution of moisture far outweighed that of dry bulk density. Shipton (2008) reported a linear relationship of SH with water content in the range 0.15-0.35 g g^{-1}. SH in water content range from 0.10-0.45 g g^{-1} appears to follow an inverse power relationship (Figure 7.3).

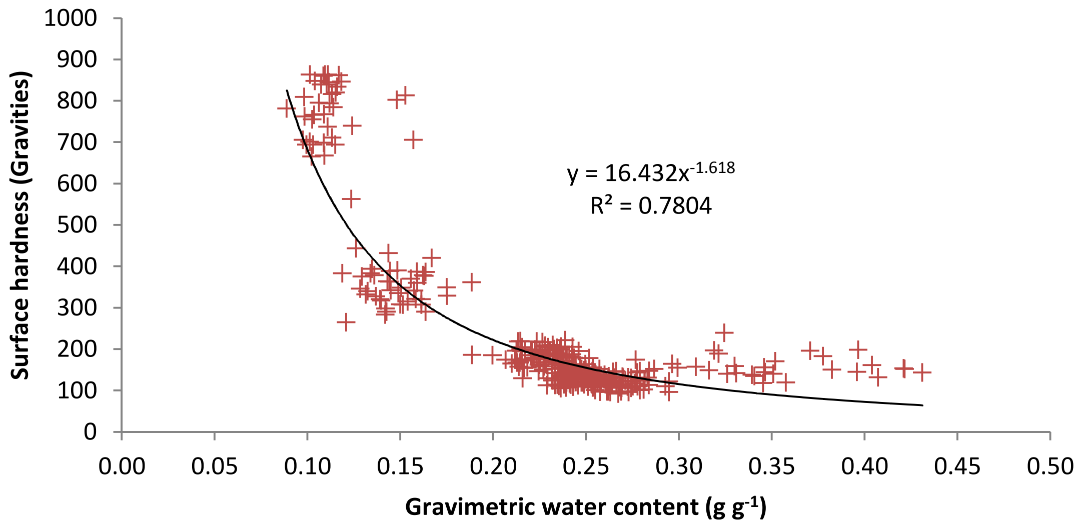


Figure 7.3 Surface hardness against gravimetric moisture content for Soil K and Soil O. Test area October 2008-February 2011.

Over the moisture content range tested by Shipton (2008) (Figure 7.4, Table 7.4) this could easily be interpreted as a linear relationship indicating broad agreement between the two results.

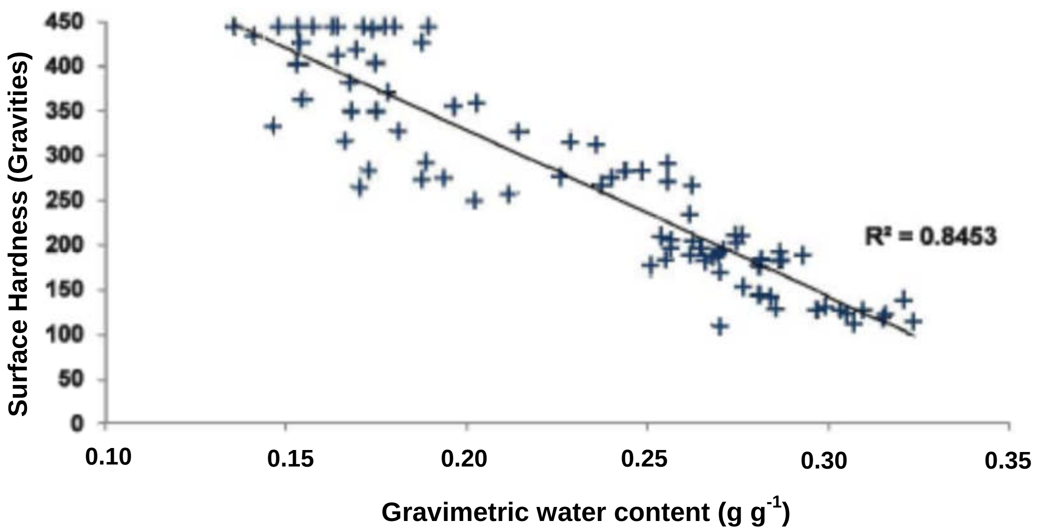


Figure 7.4 Surface hardness against gravimetric moisture content for Soil K and Soil O. Test area 2006-2007 (Shipton, 2008).

Table 7.4 Multiple regression model for surface hardness (Gravities). Explanatory variables are dry bulk density and gravimetric moisture content. b* is the standardised regression coefficient (Shipton, 2008).

Explanatory variables	b^*	Regression coefficient	p-value
Intercept		98.43	<0.001
Moisture	-0.833	-1675	<0.001
Density	0.191	36697	<0.001
Summary statistics			
Multiple R		0.935	
Multiple R^2		0.874	
Adjusted R^2		0.871	
F(2,81)		281.28	
p		<0.001	

Multiple regression analysis using the natural logarithm of moisture content and dry bulk density as explanatory variables produced a significant model for the prediction of the natural logarithm of SH with much improved R^2 value (Table 7.5).

Table 7.5 Multiple regression model for natural logarithm of surface hardness (Gravities). Explanatory variables are natural logarithm of dry bulk density and natural logarithm of gravimetric moisture content. b* is the standardised regression coefficient. Contribution uses b* to calculate the relative importance of each variable to the model.

Explanatory variables	b*	Regression coefficient	Contribution	p-value
Intercept		4.07		<0.01
Moisture	-0.99	-1.81	80%	<0.01
Density	-0.25	-1.11	20%	<0.01

Summary statistics	
Multiple R	0.91
Multiple R^2	0.83
Adjusted R^2	0.83
F(2,322)	793.1
p	<0.01
Std.Err. of Estimate	0.25

This relationship demonstrates the sensitivity of SH to moisture content in particular, but also to dry bulk density which will have to be carefully considered when discussing any aeration effects.

Similar analysis of the penetrometer results was unsuccessful, all the regression models tested had low R^2 values (<0.3). It was not possible to test during the summer due to penetration resistance being too high for the equipment; this restricted the range of moisture contents causing large clustering around 0.26 g g^{-1}. If a greater range of moisture contents were available then a clearer relationship may be resolved. The good agreement of the results of Shipton (2008) in SH would indicate a good basis for assuming that the relationship between resistance to penetration found by Shipton (2008) in the same soils and over the same area between moisture content and density can be used as the basis for analysis here, particularly as the range of moisture contents in the penetrometer data are well within those tested by Shipton (2008). Like SH the penetration resistance was largely dependent on moisture content and bulk density explaining 76% of the variation found, of which 86%

was due to moisture content, so unless in conditions of constant moisture content, penetration resistance cannot be used as a measure of bulk density and both must be considered carefully when discussing the results of the penetrometer data.

7.2 Immediate effects of aeration

Measurements of penetration resistance and surface hardness (SH) taken immediately before and after treatment for five different aeration methods are examined. The treatments showed inconsistent effects from year to year affected by weather and soil conditions at time of treatment. Generally the treatments were not affected by soil type except for Air Injection which showed contrasting actions between the two soils tested. Rolling and general maintenance showed a clear trend in increasing soil strength steadily throughout the duration of the trial.

7.2.1 Method

Construction and layout of the trial plots are detailed in Section 7.1 together with the machine specifications. Exact treatment dates each year varied due to equipment availability and prevailing weather conditions (Table 7.6).

Table 7.6 Treatment dates and onsite conditions during treatment. Group A: Air Injection, Solid Tine and Spiked Roller. Group B: Air Injection, Solid Tine, and Linear Aerator. Group C: Air injection and Solid Tine. PSWD is the potential soil water deficit.

Treatment	Rep	Date	Temperature (°C)	PSWD (mm)
Group A	1	03/11/2008	8.9	-31
Deep drill	1	04/11/2008	10.4	-31
Water injection	1	11/11/2008	8.0	-15
Group A	2	16/12/2008	3.7	0
Group B	1	10/11/2009	5.1	-46
Deep drill	1	04/11/2009	7.8	-52
Water injection	1	09/11/2009	4.1	-46
Group C	2	10/12/2009	6.7	0
Group B	1	02/11/2010	12.9	-19
Deep drill	1	16/11/2010	3.2	-2
Group C	2	14/12/2010	2.6	0

SH and penetration resistance were determined in all five subplots per soil for each treatment with the 0.5 kg Clegg Impact Hammer and Eijkelkamp Penetrologger as stated in Section 7.1. The data was analysed using repeated-measures ANOVA in Statistica 10 (Statsoft, USA). Soil volumetric water content was recorded using a Theta Probe (Delta-T Devices, Cambridge UK). The theta probe generates a 100 MHz sinusoidal signal over a specially designed transmission line that is extended into the soil by an array of four steel rods. The impedance of the array is determined by two variables, the ionic conductivity of the soil and the dielectric constant of the soils. The 100 MHz frequency was specially chosen to minimise the effect of the ionic conductivity leaving only the dielectric constant as the determining factor. The dielectric constant of the soil is dominated by water, the remaining components, soil particles and air, have minimal values. The impedance of the array affects the reflection of the 100 MHz wave which combines with the transmitted signal to create a standing wave. The difference in voltage between two points on the wave is measured by the probe and provides an accurate reflection of the soil water content (Miller and Gaskin, 1997).

7.2.2 Results

7.2.2.1 Water content

Comparison of the water content as measured by the theta probe for each treatment in each soil found that only in the water injection treatment was the water content significantly altered at $p<0.05$ when comparing the soil pre- and post-treatment. This is not surprising given the small time gap between sampling events for the other treatments and that water injection by its very nature would be expected to increase water content which it did by 1.91 ±0.5 cm^3 cm^{-3} on average.

The consequence of this result is that when comparing SH and penetration resistance between pre- and post-treatment, within each treatment application, water content is not a factor, however, when comparing between applications (i.e. between November and December treatments and from year to year) water content must be considered.

In the three years examined there was no significant difference in water content between the two soils as measured by the theta probe except November 2009. There was a significant difference between November and December in 2008 and 2009 but not in 2010. Between years 2008 and 2010 were not significantly different but both were significantly different from 2009 (Table 7.7).

Table 7.7 Volumetric water content of the soil at each treatment application date for each soil type as well as the mean of the two soils.

Soil type	Month	2008		2009		2010	
		Mean	St. Error	Mean	St. Error	Mean	St. Error
O	Nov	39.4	0.1	**37.7**	**0.2**	39.7	0.2
O	Dec	40.1	0.2	38.8	0.2	39.2	0.2
K	Nov	39.0	0.2	**37.2**	**0.1**	39.3	0.2
K	Dec	40.3	0.2	38.8	0.2	39.1	0.4
Mean (O & K)	Nov	39.2	0.1	**37.5**	**0.1**	39.5	0.2
Mean (O & K)	Dec	40.2	0.1	**38.8**	**0.1**	39.2	0.2

Within each application for each measurement an upward or downward trend can be attributed a positive or negative effect in terms of the objectives of aeration given constant water content. A lower penetration resistance is a positive effect and indicates a reduction in density or soil strength potentially allowing for greater infiltration, gas exchange or indicating the breaking down of compacted layers within the soil profile. An increased depth of maximum resistance would be a positive effect as it demonstrates that any compacted layers present in the pitch are potentially being broken down removing mechanical barriers to root penetration and water and gas movement encouraging deeper root systems. Reduced impact resistance is also a positive change indicating the breaking down of compaction from spring-summer rolling.

Two methods of results analysis were considered. One method is to compare the pre-treatment values to post-treatment values for each treatment individually; the second is by comparison of the pre- to post-treatment changes in the treated plots to any changes in the control plots over the same period. Often it was found that the pre- and post-treatment values of the control varied as much or more as the pre- and post-treatment values of the aeration treatments themselves. For instance in 2008 the ERP in Soil O, for Air Injection showed no change from treatment, i.e. pre- and post-treatment values were not significantly different. The corresponding value for the control however, showed a significant decrease. If the pre- and post-treatment values of ERP for Air Injection are compared directly, then zero effect from treatment would be the conclusion. If the change from treatment is compared to the change in the Control however this would lead to a conclusion that there was a net effect of increasing ERP from the Air Injection treatment as logically the resistance should have dropped if there had been no Air Injection treatment. This works on the basis that the relative behaviour of the control between pre- and post-treatment testing is what would occur were there to be no treatments in the other plots. This is the purpose of the control plot so, logically, the analysis must proceed by comparing changes to the control rather than directly comparing pre- and post-treatment values.

The absolute value of the net effect may not be exactly the sum of the change in the control and treatment. Using the same example from before, the Air Injection value pre- and post-treatment was ~20 J, whereas the Control pre-treatment value was ~25 J and post-treatment was approximately ~20 J. A drop of 25-20 J in the Control would in all likelihood not equate to a drop of 20-15 J in the Air Injection treatment plot, were no treatment to be applied, given the lower starting point, however some reduction in value would be expected. When interpreting the data it is important to consider then what contribution the treatment and the control have to the net effect when discussing the magnitude of the change.

Unfortunately due to user error the penetrometer readings from the December 2009 treatments were irrevocably lost.

The Water Injection machine was discontinued by its manufacturer in 2010 and no other machines were available for testing so there was no 2010 treatment for Water Injection.

The Spiked Roller was discontinued in favour of the Linear Aerator from 2009 as the Linear Aerator is more widely used as an autumn aeration treatment (Section 3) and the Spiked Roller had minimal effect.

7.2.2.2 Soil properties converge over the trial period

Prior to any treatment in October 2008, the two soils were significantly different ($p<0.05$) in ERP, MRP, DMR and SH with Soil O showing the greater value in all save DMR where it was shallower than Soil K (Table 7.8).

Table 7.8 Mean ERP, MRP, DMR and SH prior to treatment in November 2008 across all treatment plots for Soil O and Soil K.

Soil type	ERP (J)		MRP (MPa)		DMR (cm)		SH (gravities)	
	Mean	St. Error	Mean	St. Error	Mean	St. Error	Mean	St. Error
O	25.3	0.9	1.7	0.1	6.0	0.4	168.4	2.6
K	23.1	0.7	1.5	0.0	9.0	0.6	143.9	2.2

By November 2010 there were no significant differences between the two soils in any property (Table 7.10).

Table 7.9 Mean ERP, MRP, DMR and SH prior to treatment in November 2010 across all treatment plots for Soil O and Soil K.

Soil type	ERP (J)		MRP (MPa)		DMR (cm)		SH (gravities)	
	Mean	St. Error	Mean	St. Error	Mean	St. Error	Mean	St. Error
O	38.7	0.9	2.4	0.1	5.1	0.2	187.1	2.7
K	38.7	0.9	2.4	0.1	4.7	0.2	179.8	3.0

Both the ERP and the MRP tend toward greater magnitude in both soils over the time period. In addition to this the DMR moves upwards through the profile and SH increases with each successive year. Changes in Soil K tend to be of greater magnitude than Soil O. Possible causes for these changes could be the aeration treatments, or the rolling and general maintenance done throughout the year. As the same trends are distinctly visible in the control data this rules out aeration as the cause (Figure 7.5).

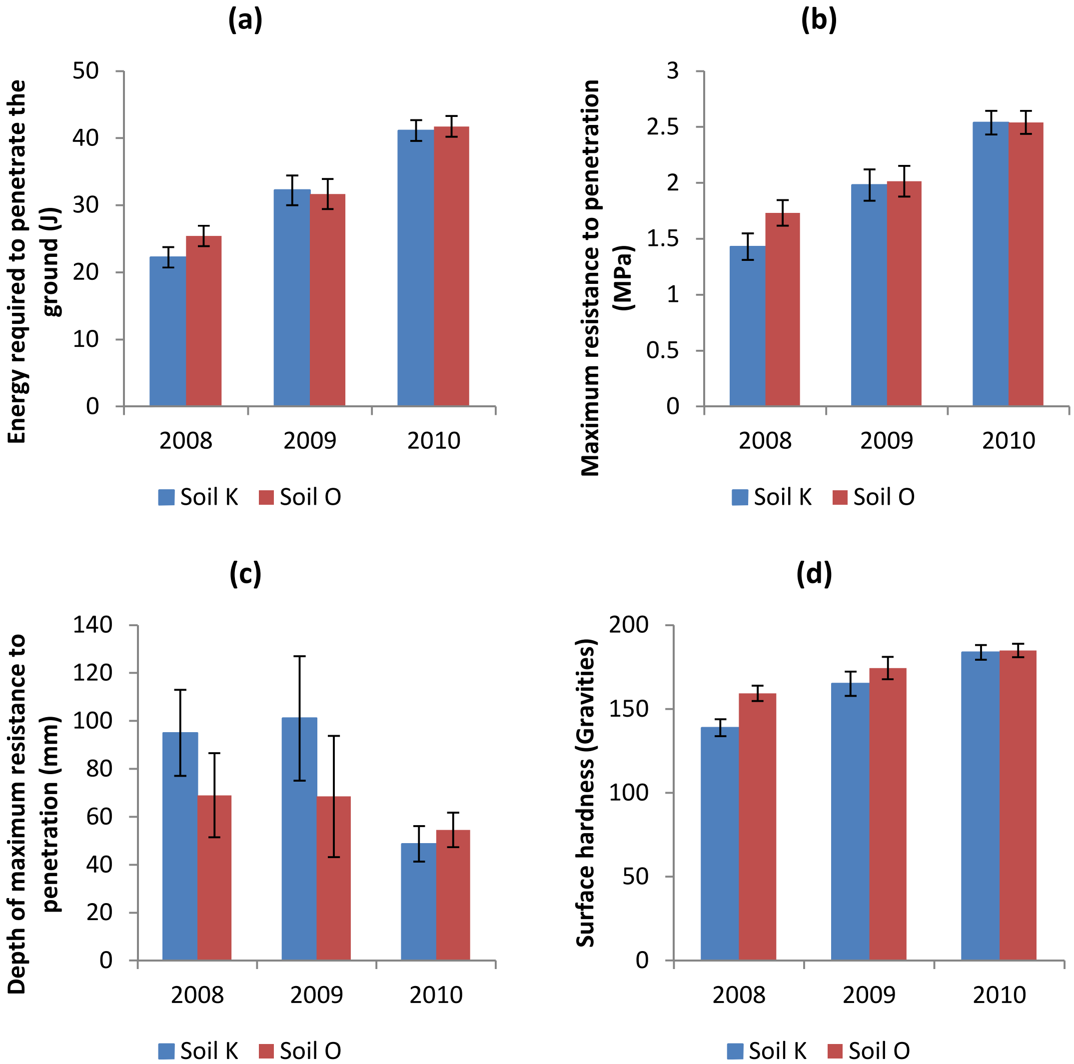


Figure 7.5 Mean values for the control area for energy required to penetrate the soil (a), (b) maximum resistance to penetration, (c) depth of maximum resistance to penetration and (d) surface hardness over time for Soil O and Soil K. Vertical bars denote standard error.

The same general trends are seen for each treatment as were present in the average data as illustrated in Figure 7.6 and Figure 7.7.

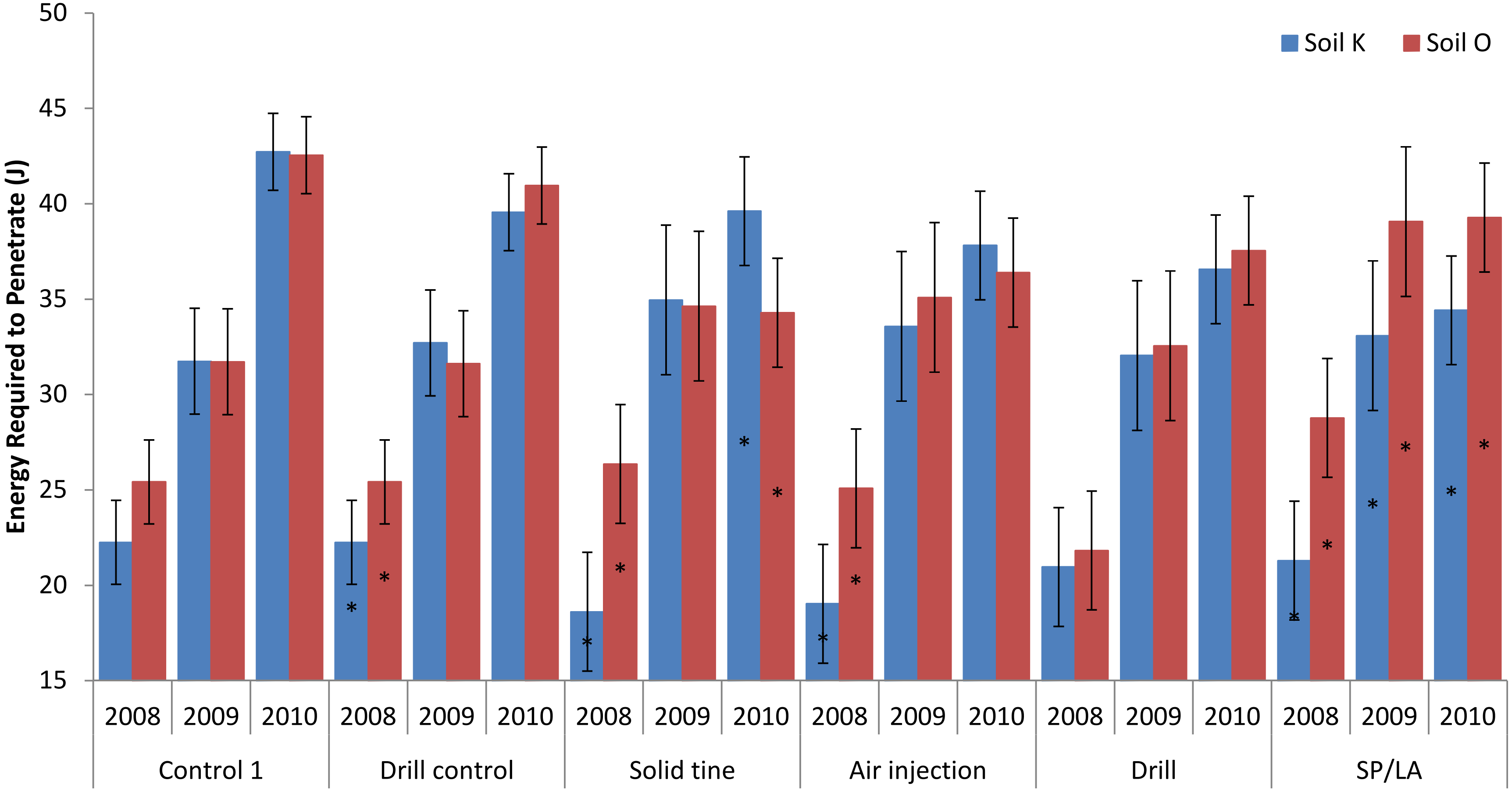


Figure 7.6 Energy of penetration over time for each treatment and soil. ✱ indicates significant difference between soils (p<0.05). Vertical bars denote standard error.

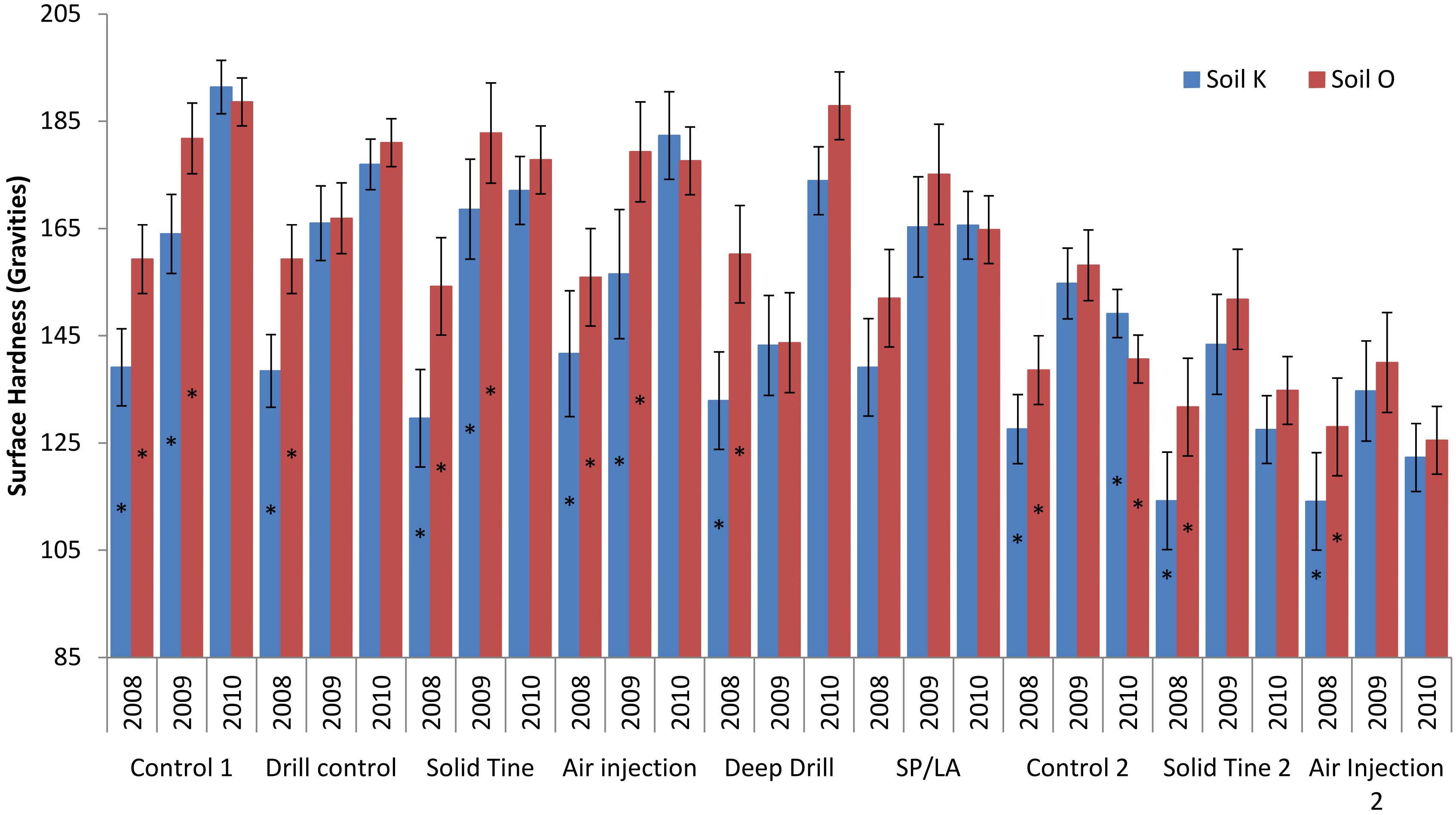


Figure 7.7 Surface hardness over time for each treatment and soil. ∗ indicates significant difference between soils (p<0.05). Vertical bars denote standard error.

7.2.2.3 Second treatments have no additional benefit

Table 7.10 compares the changes in the Control pre- and post-treatment to the changes in treated plots pre- and post-treatment for each parameter in each year. Numerous effects were noted in the initial treatments particularly for Solid Tining and Air Injection.

Table 7.10 Significant Time*Treatment*Soil type and Time*Treatment interactions when compared to changes in the Control. Brown squares are Time*Treatment*Soil type effects, green squares are Time*Treatment, i.e. no soil type difference. ⬆ is increase in variable after treatment, ⬇ decrease in variable after treatment (p<0.05).

Treatment	Soil	2008				2009				2010			
		ERP	MRP	DMR	SH	ERP	MRP	DMR	SH	ERP	MRP	DMR	SH
Air injection	O	⬇	⬇						⬇	⬆	⬆		⬆
	K	⬆	⬆						⬇	⬇	⬇		⬆
Solid tining	O	⬆	⬆				⬇		⬇	⬇	⬇	⬆	⬆
	K	⬆	⬆				⬇		⬇	⬇	⬇	⬆	⬆
Drilling	O												
	K												
Water injection	O								⬇				
	K								⬇				
Spiked Roller	O												
	K												
Linear Aerator	O								⬇				⬆
	K								⬇				⬆
Air injection 2	O												
	K												
Solid tining 2	O												
	K								⬆				⬇
Spiked Roller 2	O				⬆								
	K				⬆								

7.2.2.4 Air injection

Air Injection showed contrasting behaviour in each soil in both ERP and MRP. In Soil O the ERP and MRP decreased in 2008 and increased in 2010 relative to the Control (Figure 7.8 (a) & (c)).

Soil K showed the opposite behaviour increasing in 2008 and decreasing in 2010 (Figure 7.8 (b) & (d)) with the addition of a decrease in MRP in 2009. Generally, the net changes observed in Soil O are caused by changes in the value of the treated plots as the difference between pre- and post-treatment values of the control are small. In Soil K the pre- to post-treatment values for the control show greater change than the Air Injection which are generally smaller but overall make a significant net difference.

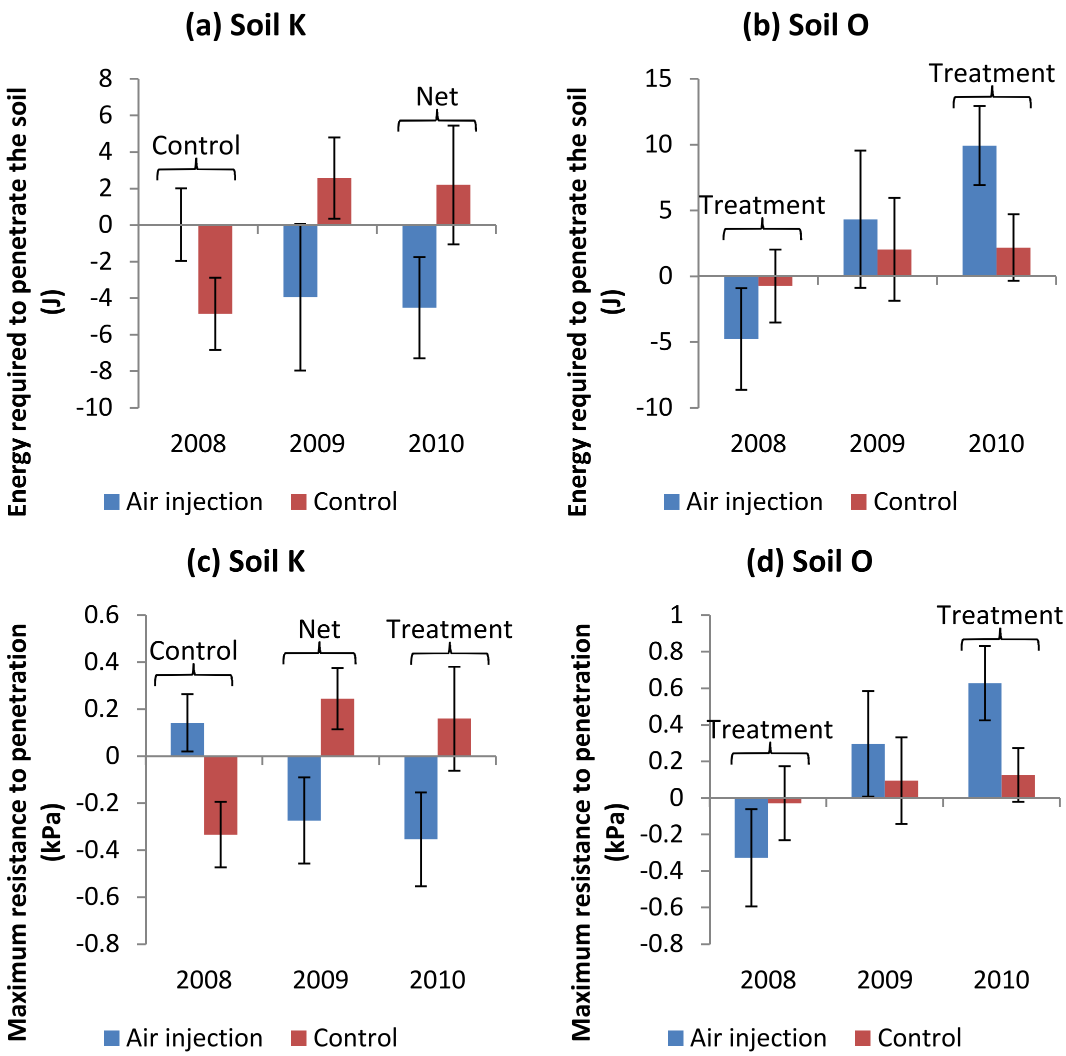


Figure 7.8 Comparison of the change in the energy required to penetrate the soil after treatment to before treatment for Air Injection and Control in Soil K (a) and Soil O (b); comparison of the change in the maximum resistance to penetration after treatment to before treatment for Air Injection and Control in Soil K (c) and Soil O (d). Vertical bars denote standard error. Labels indicate primary driver of the observed effect whether the control is changing or the treatment. The 'Net' label indicates that neither the control nor the treatment showed a significantly different value from pre- to post-treatment but did show a significant net difference in post-treatment values between control and treatment that was not present in pre-treatment values.

The behaviour from year to year in each soil fluctuated. In ERP and MRP the behaviour in each soil inverted between 2008 and 2010. For surface hardness

(SH) the decrease in 2009 became an increase in 2010 (Figure 7.9). The differences between 2009 and the other years could be due to the reduced water content that year but differences between 2008 and 2010 are harder to explain given the similar water contents.

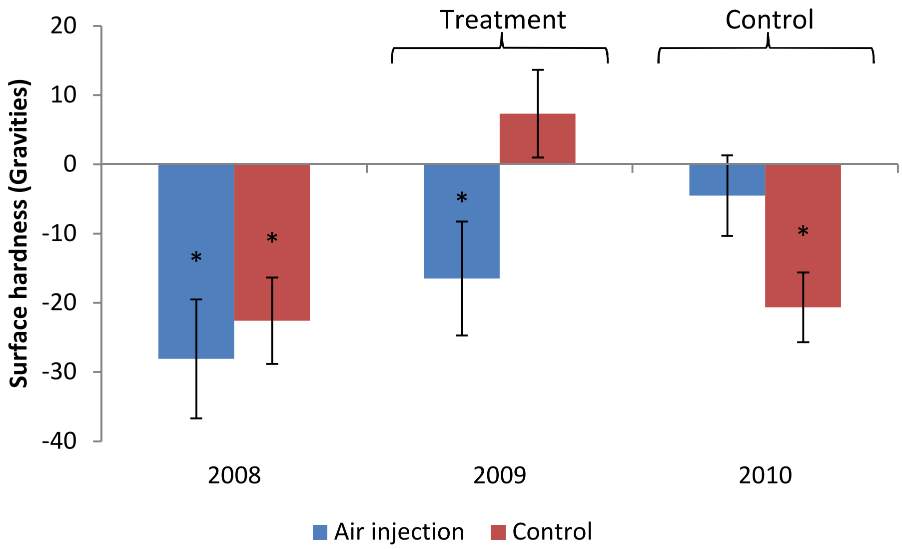


Figure 7.9 Comparison of the change in surface hardness after treatment relative to before for Air Injection and Control treatments averaged over both soils. ∗ indicates a significant difference between pre- and post-treatment values at p<0.05. Vertical bars denote standard error. Labels indicate primary driver of net observed effect.

Two significant effects were observed in Soil K in the depth of maximum resistance to penetration from Air Injection. In 2008 and 2010 the depth of maximum resistance was moved to a greater depth from treatment (Figure 7.10). This effect was also observed in Section 7.3. Soil O was unaffected by aeration treatment.

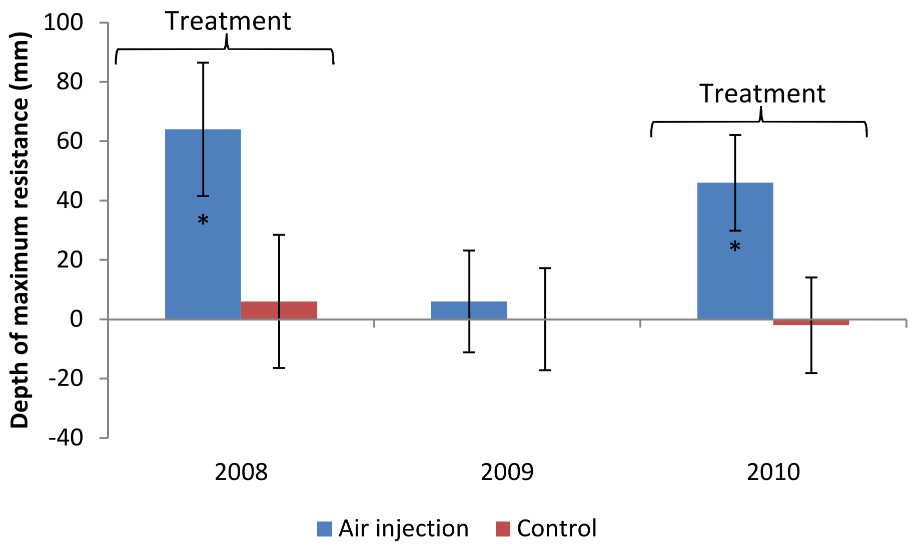


Figure 7.10 Change in the depth of maximum resistance in the control and Air Injection each year. ∗ indicates a significant difference between pre- and post-treatment values at p<0.05. Vertical bars denote standard error. Labels indicate primary driver of net observed effect.

7.2.2.5 Solid tining

Solid tining shows the most consistent effects between soils (i.e. there were no significant differences between the behaviour in each soil).

Noticeably the Solid Tine treatment follows the same general trends as Air Injection in Soil K (Figure 7.11 (a) & (b)) for ERP, MRP and SH:

- In 2008 the net effect is primarily driven by the difference between Control values rather than the Solid Tine treatment.
- 2010 in ERP the same effect of treatment decreasing and control increasing, as seen in Air Injection in Soil K, gives a net reduction from Solid Tining.

Solid Tining differs from Soil K Air Injection in that there is no observed movement in DMR and in Air Injection there was no observed decrease in MRP in 2009 from treatment (this effect is driven by changes in the control value rather than the treatment however).

The effect on surface hardness in both soils is very similar between Air Injection and Solid Tine, both follow the same general trends (Figure 7.11 (c)). Again the effects between the years were inconsistent flipping from positive to negative both for the treatment effect and the control.

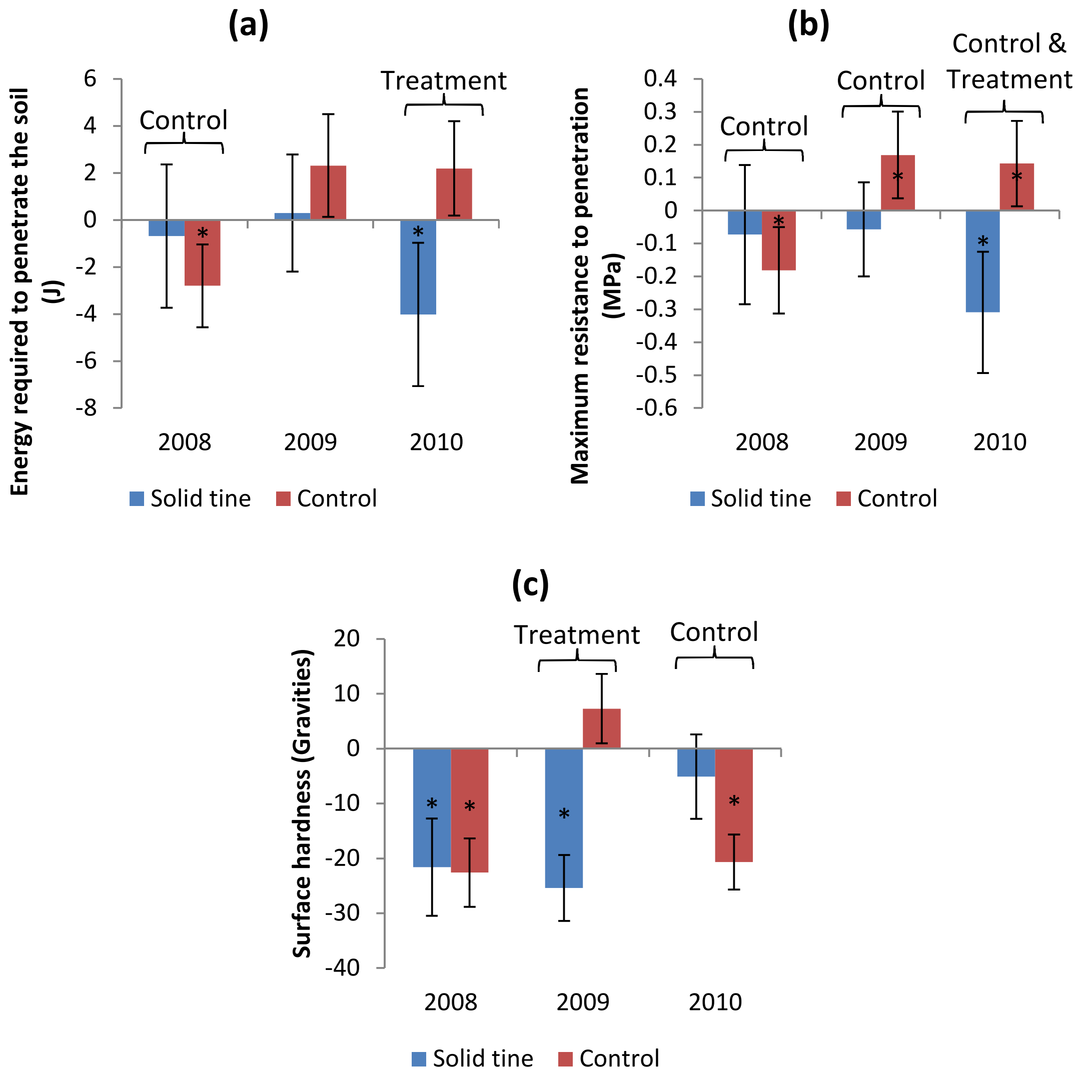


Figure 7.11 Comparison of the change in ERP (a), MRP (b) and surface hardness (c) post-treatment relative to pre-treatment for Solid Tine and Control treatments averaged over both soils. ∗ indicates a significant difference between pre- and post-treatment values at $p<0.05$. Vertical bars denote standard error.

The repeat treatments in December showed much smaller changes between pre- and post-treatment values both for the Solid Tine and for the Control (Figure 7.12). Only surface hardness showed a significant effect and only in

2009 and 2010. In 2009 the Control decreased significantly in surface hardness but the treatment remained constant resulting in a net negative effect. In 2010 the treated area showed significant reduction in surface hardness resulting in a net positive effect.

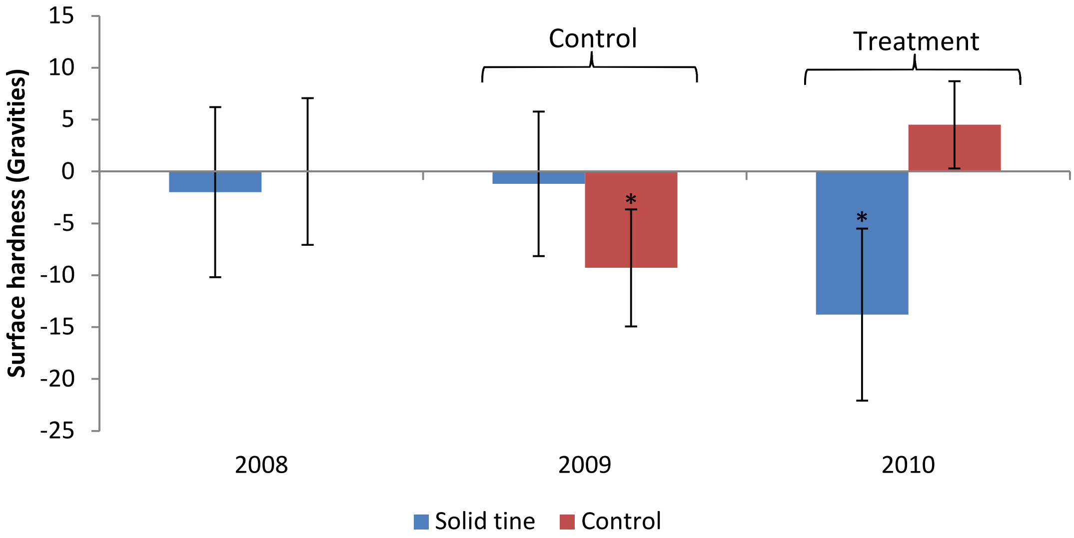


Figure 7.12 Change in surface hardness for December treatments of Solid Tine and Control from pre- and post-treatment in Soil K. ∗ indicates a significant difference between pre- and post-treatment values at p<0.05. Vertical bars denote standard error.

7.2.2.6 Deep drill

The Deep Drill showed no effects on any of the soil properties measured in each year. The difference from pre- to post-treatment either followed the same general pattern as the control on each occasion or was so small relative to the standard error that no significant difference was observed (Figure 7.13).

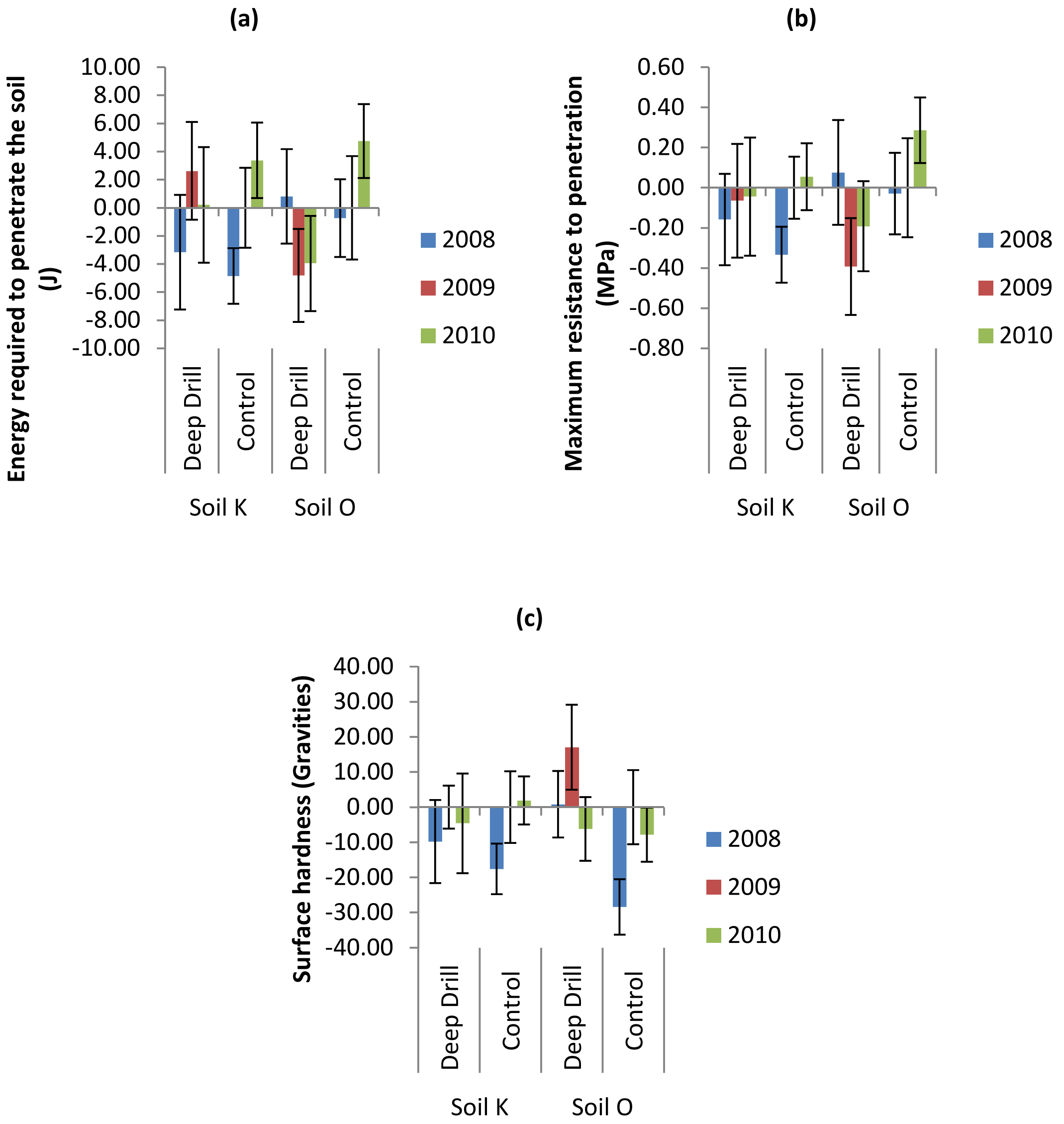


Figure 7.13 Difference between pre- and post-treatment in the control and Deep Drill for each year in (a) energy required to penetrate the soil, (b) maximum resistance to penetration, (c) surface hardness. Vertical bars denote standard error.

7.2.2.7 Water injection

The Water Injection treatment showed no net effects in 2008 on any properties measured. In 2009 this treatment caused a decrease, in both soils, in SH (Figure 7.14), with the change primarily driven by the treatment itself rather than a change in the control. There was a significant decrease in surface hardness from the Water Injection treatment in 2008 but as the control also decreased the final values of the control and Water Injection treatments were not significantly different, so there was no net effect. In 2009 there was also a decrease in the control but the decrease recorded from treatment was greater giving a net decrease in surface hardness from Water Injection treatment.

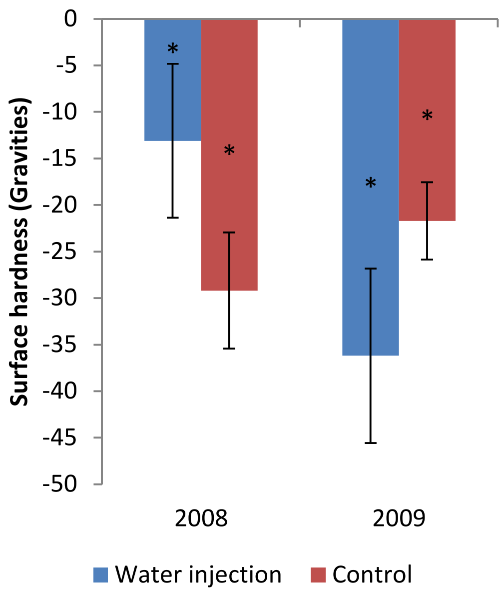


Figure 7.14 Comparison of the change surface hardness after treatment relative to before for Water Injection and Control treatments averaged over both soils. ∗ indicates a significant difference between pre- and post-treatment values at $p<0.05$. Vertical bars denote standard error.

7.2.2.8 Linear Aeration and Spiked Roller

The Spiked Roller showed no effects in 2008 and a minor change in surface hardness in December of the same year. This treatment was then discontinued in favour of the more recent and increasingly popular linear aeration treatment from 2009 onwards.

In 2009 Linear aeration showed benefits in terms of reducing surface hardness. In 2010 the opposite effect was found as the Linear Aeration treatment did not significantly alter surface hardness whereas the control showed a significant decrease.

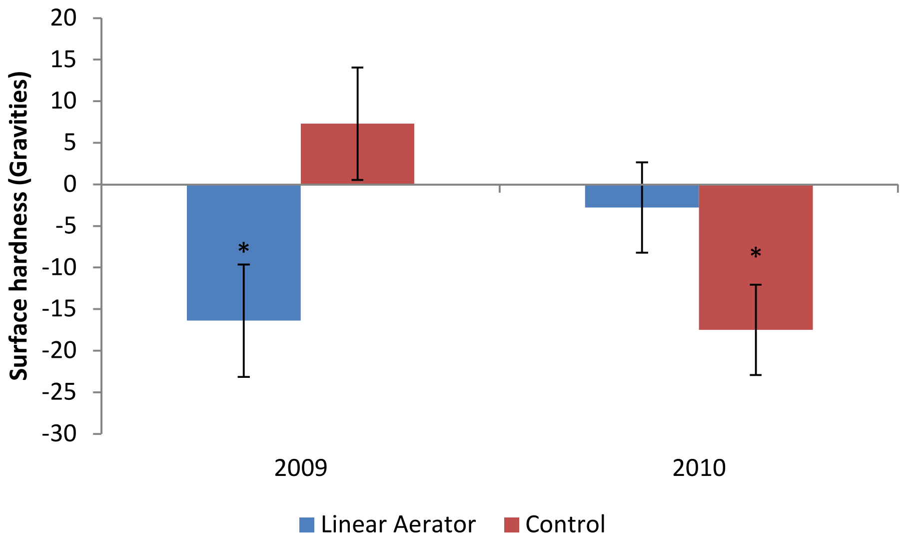


Figure 7.15 Comparison of the change in surface hardness after treatment relative to before for Water Injection and Control treatments averaged over both soils. ∗ indicates a significant difference between pre- and post-treatment values at p<0.05. Vertical bars denote standard error.

7.2.3 Discussion

Only a small body of research exists for the evaluation of aeration in soils and almost all of it is exclusively focused on sand dominated soils based around the USGA specifications for golf course construction. Much of the research centres on hollow core tining which is commonly used on golf courses to relieve compaction and remove organic matter by replacement with fresh soil (Murphy *et al.*, 1993; Carrow, 2003; McCarty *et al.*, 2007; Murphy and Rieke, 1994).

Prämaßing *et al.* (2009) found in a loamy sand that the effects of Solid Tine cultivation and Water Injection sometimes decreased penetration resistance but could also increase it. This was attributed to changing soil conditions on treatment application. Morhard and Kleisinger (2004) found that finer soils (a sandy loam compared to a sand) showed shorter-lived effects from aeration than coarser soils but overall aeration gave positive effects, reducing penetration resistance and increasing oxygen concentrations.

7.2.3.1 Soil properties converge over the period

Given that each treatment shows the same pattern of converging soil properties (including the Control) it is unlikely that the cause of the convergence is driven by aeration treatments, although the variation between treatments suggests that some aeration techniques may have an influence but this is small compared to the overall trend. As the convergence is seen in every trial plot the cause of it must be something that affects all of them at least broadly equally. Two possible all-plot factors are the weather and the general maintenance (including seasonal rolling) done throughout the year. In this case the trends observed in each property can be logically linked to a consistent and effective rolling treatment across the test area; the increasing ERP, and MRP, the migration of the depth of maximum resistance to a shallower depth, and increasing surface rebound can all be attributed to the compression of soil by rolling which is primarily focused in the top 50 mm of the soil profile (Shipton, 2008). Given that the same trend is observed across all treatment plots and that in Section 7.3 it was found that the bulk density was generally unaffected by aeration it can be concluded that there was no aeration interaction with rolling. Generally the effects of aeration are small, where observed, which could be why there were only a small number of observed effects, whereas rolling shows a clear definitive compacting action on the soil (Shipton, 2008) the effect of aeration on which is either none existent or negligible in comparison. The weather would primarily effect the measurements via the water content which did not vary in a pattern consistent with the trend observed as the soil was slightly drier in 2009 compared to 2008 and 2010; if the weather was the cause the drier soil of 2009 would be expected to show a peak in soil strength and thus a peak in the three properties as all are an indirect measure of soil strength. The potential soil water deficit (PSWD) from 2008-2010 shows considerable variation from year to year. The PSWD for each treatment date, like water content, would lead to a conclusion that if it was weather derived then 2008 and 2010 would be expected to show similar results and 2009 to be different which is not the observed effect (Figure 7.16).

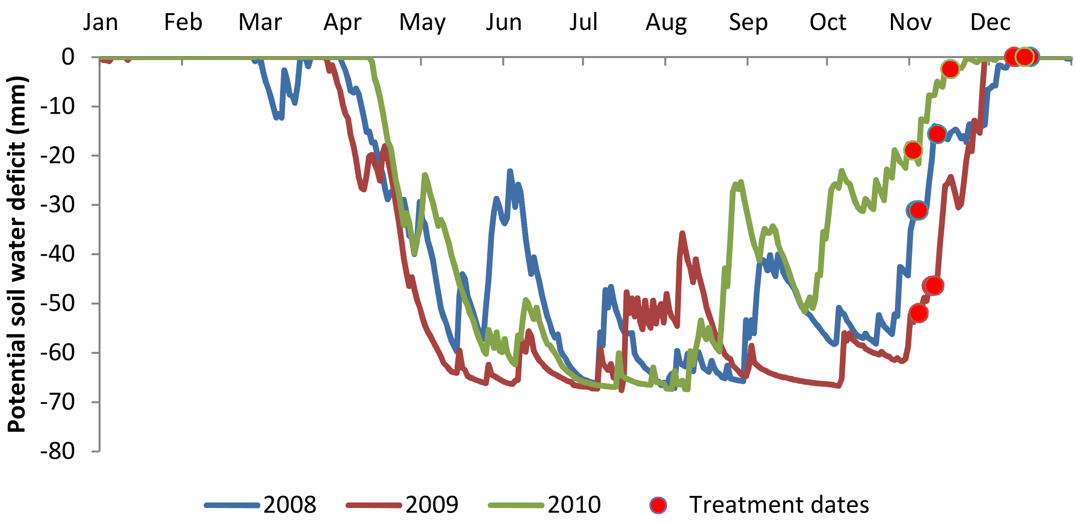


Figure 7.16 Potential Soil Water Deficit (PSWD) during the experimental period.

The pattern of PSWD over the course of each year also does not corroborate a weather derived theory as the generally much drier 2009 would show distinctly less wetting and drying cycles than 2008 and 2010 which show distinct wetting and drying from the jagged peaks in the data which would lead to a conclusion of 2008 and 2010 being similar again or showing reduced soil strength relative to 2009 instead of the steady climb that is seen in the data.

7.2.3.2 Second treatments are ineffective

Of the four treatments that were repeated in December each year, only two showed any effects, Solid Tining and Spiked Roller, and only in surface hardness. The relative values of the changes induced in surface hardness by Solid Tining were much smaller in December than they were in November indicating that any effects that do occur from aeration are weaker than their November equivalents.

There was a significant difference between the average water content in November and December across all treatments and time. The average water content in November was 38.8 ± 0.2 %v, the average water content in December was 39.3 ± 0.1 %v. Prämaßing *et al.* (2009) found that the water content influenced the effectiveness of aeration treatments in sand. However, the changing water content does not completely explain the lack of repeat treatment effectiveness in these finer soils. The soil water content in December 2010 was not significantly different from the water content in November 2008 and November 2010 (Figure 7.17). November 2008 and November 2010 showed considerable aeration effects from the Air Injection and Solid Tine treatments which were not seen in December 2010 (Table 7.10). Thus water content alone cannot explain the behaviour seen here.

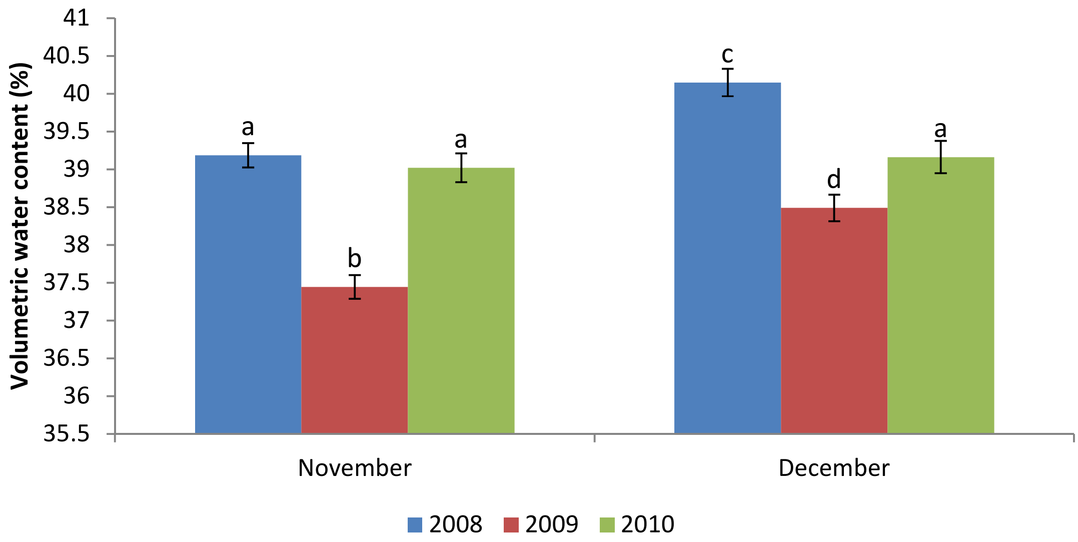


Figure 7.17 Mean volumetric water content of Soil O and Soil K each year for the two treatment times. Letters indicate homogenous groups (p<0.05). Vertical bars denote standard error.

Prämaßing *et al.* (2009) found that the action of frost caused considerable loosening of the soil and a reduction in soil strength. Soil O and Soil K will, in addition to the effect of frost, exhibit shrink-swell behaviour (Section 4) which was demonstrated by Shipton (2008) to reduce dry bulk density in both soils to a depth of 120 mm. Across all treatments the surface hardness drops significantly between the initial treatment and repeat treatment indicating the effect of frost and shrink-swell (Figure 7.18). The softer soil in December each year would likely be more susceptible to compaction from the compressive weight of the treatment machines which was seen in the Spiked Roller treatment which did not affect the either soil in November 2008 but caused a slight increase in surface hardness in December 2008 indicating increased surface compaction from treatment. The Air Injection and Solid Tine machines were larger and heavier and so would be expected to cause more surface compaction than the Spiked Roller which was not observed. Either there is no compaction or alternatively the aeration treatments themselves negate the effect of compaction in Air Injection and Solid Tine to give a generally net neutral effect that is generally unobserved.

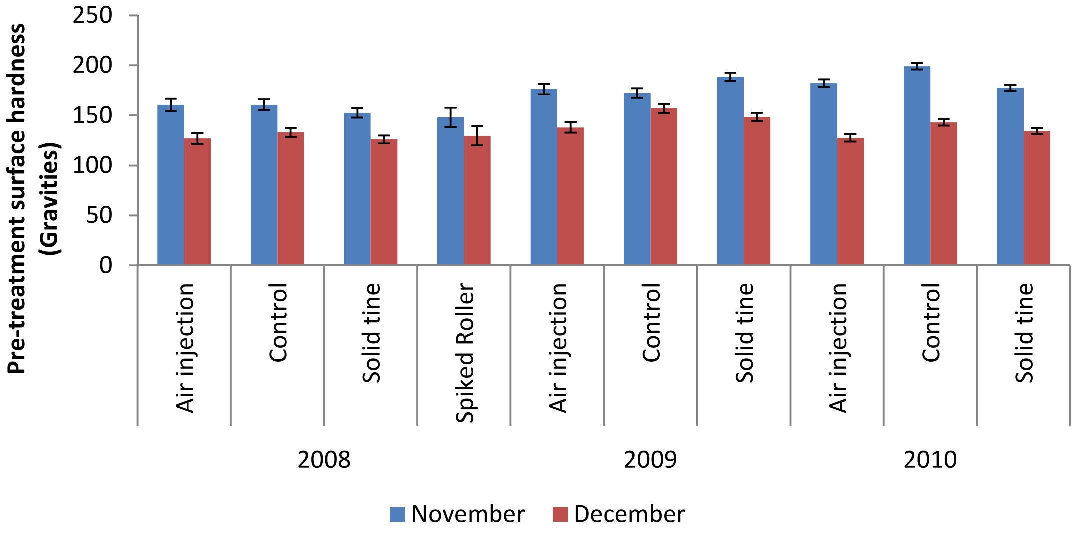


Figure 7.18 Comparison of pre-treatment surface hardness averaged over both soils for initial treatment in November and repeat treatments in December. Vertical bars denote standard error.

The Solid Tine December treatments have the opposite effect on SH of the November treatments but only in Soil K; Soil O is seemingly unaffected by the repeat treatment. In 2010 the change in surface hardness in November was caused by a drop in the value of the Control from pre-treatment to post-treatment rather than a change in the Solid Tine plot. Conversely, the change in December 2010 was driven by a drop in surface hardness from pre- to post-treatment for Solid Tine with the Control unchanged. 2009 was basically the opposite of 2010, with the November change in surface hardness caused by a reduction in the Solid Tine plot, and the December change caused by a reduction in the Control plot. In 2009 the average ambient temperature between the two treatment dates were relatively mild with a mean over the whole period of 8.6 °C and only a single day out of 30 where the minimum temperature was below 0 °C. In contrast in 2010 the temperatures were generally lower and the December treatments were preceded by a period of very low temperatures (Figure 7.19). The mean temperature over the 2010 period was 3.7 °C with 20 out of 42 days with minimum temperatures below 0 °C. Clearly the weather plays a key role, particularly freezing temperatures potentially causing frost heave that will act to decompact the soil. The mild weather meant the reduction between pre-treatment values in November and December in 2009 was smaller than the value for 2010. Though why the harder soil in December 2009 should increase in surface hardness from Solid Tining whereas the softer soil in 2010 should decrease is unclear.

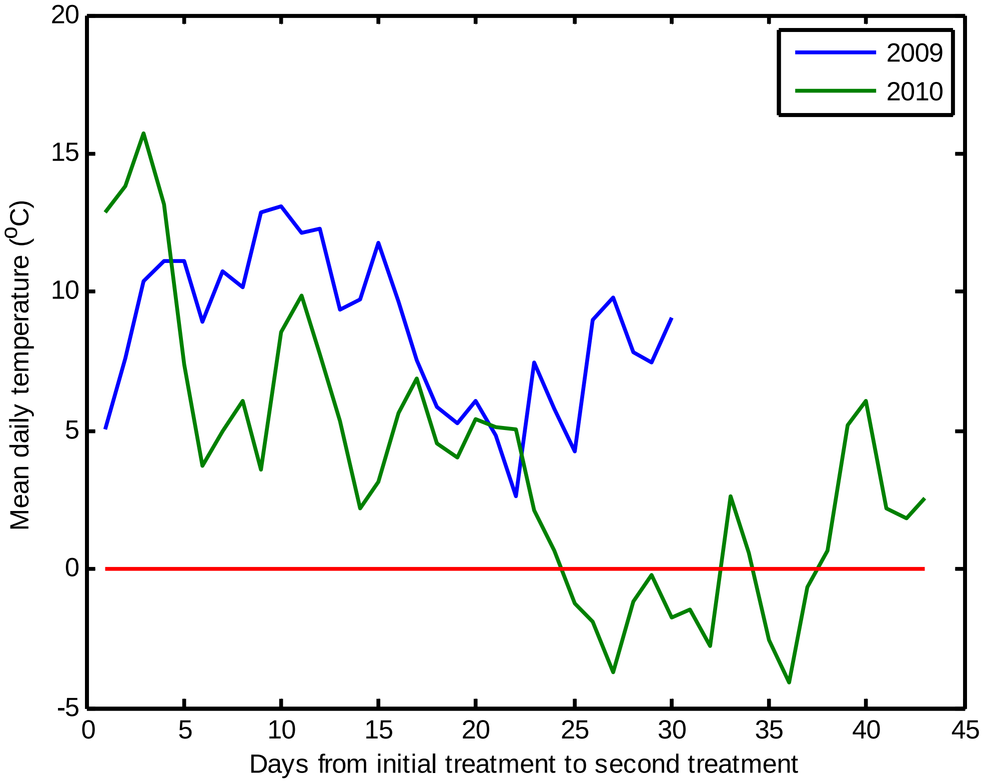


Figure 7.19 Mean daily temperature between November and December treatments in 2009 and 2010. Data from Clifton Weather Station, distance approx. 5.5 miles from trial plots. Note there are 30 days between treatment in 2009 and 42 days in 2010.

7.2.3.3 Air injection & Solid tining

Air Injection in Soil K and the Solid Tine in both soils showed the same general effects, particularly for surface hardness. The mode of action of the two machines is very similar, both drive a solid tine vertically into the soil and retract it and penetrated to the same working depth of 90 mm. The Air Injection machine has the additional action of releasing a short burst of compressed air when the tine reaches maximum penetration possibly expanding the working depth of this technique. Given the similarity of the Solid Tine and Air Injection treatments in Soil K the compressed air component of the Air Injection treatment is the most likely cause for the movement of DMR under Air Injection rather than the action of the tines directly.

The compressed air exudation is the only factor differentiating the modes of action of the Solid Tine and Air Injection treatments so it must be this that causes the disparate effects in the two soils under Air Injection. Soil O showed opposite effects to Soil K in ERP and MRP for Air Injection in 2008 and 2010 but the same effects on surface hardness for all years. Surface hardness is a measure that is primarily affected by the upper layers of soil. Given that surface hardness follows the same trends as Solid Tining in Soil O the effect of the air blast must be lower down the profile (as expected given it is delivered at maximum penetration) which in Soil O reverses the general trend caused by Solid Tining alone in ERP and MRP and does not affect DMR as in Soil K. The water content of the soil in each treatment area within each year was not significantly different and exceeded the plastic limits determined by Shipton (2008) for both soils.

The explanation for this behaviour is related to the pore size distribution of the two soils and is discussed in Section 7.3 with the addition of further data.

7.2.3.4 Deep Drill

The Deep Drill machine had no effect on any of the properties measured. The machine cuts its way into the soil, removing soil as the drills enter the ground minimising compaction around the tine hole as the soil is excavated rather than displaced. This is in contrast to the thrusting action of Air Injection and Solid Tining which act only to displace the soil creating compaction around the tine holes. As a consequence the immediate effects of the Deep Drill may not be apparent particularly as mechanical testing was done between tine holes. This does not necessarily mean that the Deep Drill treatment has no effect on the soil only that the limited range of soil parameters tested here did not observe one. The Deep Drill may affect root density, gas exchange capability, and evaporation through increased surface area that is not tested here. The efficacy of the Deep Drill for the amelioration of layering in the profile cannot be tested here and so cannot be ruled out.

7.2.3.5 Water injection

The Water Injection treatment effectiveness is strongly linked to water content of the soil prior to treatment. In 2008 when the soil had greater water content than in 2009 there were no treatment effects. In contrast in 2009 only the depth of maximum resistance was unchanged, all other measures showed a decrease indicating reduced soil strength from treatment. Given that the treatment involves pumping water at high pressure into the soil the water content of the soil will be increased and consequently the soil strength will decrease. It is not possible to definitively state with the instruments used whether the observed effects are entirely due to increased water content or whether the high pressure delivery of the water into the soil also affects the readings due to the high sensitivity of the measured variables to water content. Consequently this treatment cannot be said to have no effect beyond what would be achieved by heavy irrigation of the pitch to increase water content in terms of its immediate effects. However, given that there were no observed effects in 2008 when the soil had a greater water content than in 2009 it would seem likely that most of the effects are driven by increased water content rather than the action of the treatment itself otherwise if the effects were caused by the action of the high pressure injection observable effects would have been expected in 2008.

7.2.3.6 Linear Aerator

Unfortunately only two years of trial data exist for this treatment and there is no clear trend between the two years. The only observed effects were in SH. Given that the penetrometer measures over a depth of 150 mm and the working depth of this machine is only 20 mm mainly surface effects would be expected. Once again water content seems to play a key role as in 2009 when the soil was drier Linear Aeration caused a reduction in surface hardness but in 2010 the same treatment caused an increase in surface hardness. The difference in water content between the two years was small (~0.5%). Visual and tactile observation of the soil in both years found it soft, pliable and in a plastic state.

The soil did not shatter when the blades passed through it but rather was deformed or removed. If the soil had been so dry in 2009 that it shattered when the blade passed through it then a water content driven explanation would explain the reduction in surface hardness. As both years the soil was soft and deformable this cannot be the case. Possibly the slightly wetter, slightly weaker soil in 2010 was compressed by the weight of the machine more than the drier, stronger soil in 2009. In this situation the work done to reduce surface hardness in 2010 is undone by the compressive force of the weight of the machine. In 2009 the slightly stronger soil is more able to withstand the compressive weight of the machinery and so the treatment has a greater net effect.

7.2.3.7 Method limitations and suggestions for future work

All of the instruments used are an indirect measurement of soil strength. The reduction in soil strength from aeration is just one of several factors that aeration treatments are expected to have on the soil (Rieke and Murphy, 1989). Other immediate effects aeration may have included: increased gas transfer between soil and air, and increased infiltration and hydraulic conductivity. Ideally these factors would be measured as well to give a greater all round indication of aeration treatment effectiveness. Decreased soil strength can be used as an indicator for many of these properties as a lower strength soil (of the same type, stress history and water content) would be expected to have a lower bulk density, with increased pore space allowing for greater movement of liquids and gases. An actual measurement would however be better than an indication of these properties.

Possibly not all the effects of aeration are realised immediately and it is a combination of soil natural shrink and swell or the effect of increased surface area from aeration (increasing heat exchange with the atmosphere and evaporation), that leads to other effects that are not observed here. As always a compromise has to be reached with available resources and the range and frequency of testing but in an ideal world potentially a more informative view could have been gained by sampling over a period of days and weeks after aeration treatments to assess the short term effects of aeration that may have declined or disappeared prior to testing in February (Section 7.3).

The weather conditions over the year appear to have a large impact on the effectiveness of the aeration treatments, altering them from positive to negative influences from year to year. With factors stretching back over such a long time period affecting the trials it is difficult to build a concise definitive picture of how each treatment affects the soil. Trials conducted in a laboratory setting to examine the effect of the aeration treatments on more closely controlled soil conditions at different water contents and densities would help solve the interaction of treatments with these factors that cannot be elucidated clearly from these trials.

7.2.4 Summary of the key points on the immediate effects of aeration

The most noticeable trend in the data is the very changeable effects that each process has from year to year. Each treatment, apart from Water Injection and the Deep Drill, show different effects on the soil from year to year, some positive and some negative, and all treatments (except the Deep Drill) have no effects in some years that will appear the next year or were present in the previous year. There seems to be no consistency to the effects of aeration treatments. All of this is closely linked to the conditions of the soil at the time of treatment. However the conditions are not limited to just water content and density as the shrink swell nature of the soil and the action of freezing conditions also play a vital role such that judging whether a treatment will be effective is only possible by examining a large range of factors over an extended period and even then it is hard to tell what the actual effect of the selected treatment will be as it has proven so difficult to explain the behaviour of the treatments here.

The most consistent trends in the data have come from processes outside of the aeration treatments. Seasonal rolling over three years resulted in a general increase in all attributes. Whilst shrink-swell and frost heave have resulted in a consistent decrease in surface hardness between November and December across all three years – the action of which appears to render repeat aeration treatments (within a single season) almost completely ineffective and in some instances damaging.

The effect of Air injection was found to be significantly different at depth than the Solid Tine but showed similar surface effects. The difference at depth is dependent on soil type and is discussed further in Section 7.3 and resulted in opposite trends in ERP and MRP in 2008 and 2010 between the two soils and in the same years caused the DMR in Soil K to move deeper in the profile.

The Deep Drill showed no effects on the properties measured and similarly the effects of the Water Injection treatment seemed to stem from increased water content rather than a definitive treatment effect. However this may reflect more the limited range of measurements rather than a lack of treatment effects.

The Linear Aerator showed only surface effects related to the shallow working depth of the treatment.

Whilst this Section only examines the immediate effects of aeration an interim conclusion based on the evidence so far indicates that the changes induced by aeration are minor compared to the natural processes that relieve the soil compaction over the winter months as evidenced by the lack of clear benefits from aeration treatments consistently through the three years and the sparsely detected alterations by aeration on the soil. Potentially, over a longer period of time the treatments have as yet undetected benefits such as increasing surface area for evaporation and heat exchange resulting in increased shrink and swell and frost heave which is explored in the next Section but in the short term nature seems much more reliable in relieving soil compaction than aeration except for the possible action of Air Injection in certain soils.

7.3 Long term effects of aeration

Measurements of soil physical and biological parameters were taken every four months to assess the long term impact of five different aeration treatments with the aim of assessing six main hypotheses:

1. Aeration will decrease bulk density by creating extra pore space for shrink and swell to the machine's working depth.
2. Aeration will increase bulk density at the treatments working depth due to compaction of the soil by the tines (except Deep Drill).
3. Aeration will decrease water content due to increased surface area and increased hydraulic conductivity.
4. Aeration will increase water content due to increased infiltration and the capturing of surface run-off in tine holes.
5. Aeration will increase Microbial (MC) Biomass due to increased oxygenation
6. Increased MC Biomass will assist the breakdown of organic material reducing the organic matter content of the soil.

7.3.1 Experimental Approach

Details on test area layout and construction and aeration treatments used are discussed in Section 7.1.

Every four months from October 2008-February 2011 the trial plots were assessed for:

- Dry bulk density
- Water content
- Surface Hardness (SH)
- Penetration resistance
- Organic matter content
- Microbial biomass

Each trial plot was subdivided into ten equal sections 1.3 m in length along the long axis. This resulted in five subplots per soil, per aeration treatment. Soil cores for bulk density, water content, organic matter and microbial biomass were taken at random from three of the five subplots for each soil and treatment per sampling event.

SH was determined in all subplots with a 0.5 kg Clegg Impact Hammer (Clegg, 1976) dropped from 0.55 m height three times in the same location. The peak deceleration of the third drop was recorded. The June 2010 measurements were recorded using a 2.25 kg Clegg hammer as the 0.5 kg Clegg did not have sufficient range (maximum 400 gravities). Conversion from 2.25 kg Clegg Impact Hammer to 0.5 kg Clegg Impact Hammer was calculated from the calibration curve created by (Baker *et al.*, 2007) using Equation (7.1).

$$Surface\ hardness\ (0.5\ kg) = \frac{Surface\ hardness\ (2.25\ kg) - 6.2918}{0.5706} \qquad \textbf{(7.1)}$$

Each subplot was also measured for soil penetration resistance using an Eijkelkamp Penetrologger with a 30°, 130 mm^2 base area cone at 30 mm s^{-1}. The penetrometer could not be used in June of each year as penetration could not be achieved without risking damage to the unit or the user due to the high soil strength of the dry soil.

Dry bulk density and water content were determined by taking cylindrical cores using 42 mm split corer (BMS Products Ltd, Luton, UK) from the surface to the top of the sharp sand layer (approximately 200 mm deep). The cores were wrapped in plastic film and sealed in individual bags before being placed in a cool environment (<5 °C) to reduce biological activity and prevent evaporation. Each core was carefully subdivided into four sections (± 1 mm):

1. 0 mm – 25 mm
2. 25 mm – 75 mm
3. 75 mm – 125 mm
4. 125 mm – base of core

Samples were placed in preweighed tins (±0.01 g), and the combined weights recorded (±0.01 g). The soil was dried at 105 °C for 24 h and the dry weight of soil recorded (±0.01 g). These samples were then used to determine soil organic matter content using British Standard BS EN 13039:2000. Pre-weighed samples were heated to 450 °C for four hours. During this time the organic matter is expected to ignite and be released as carbon dioxide. Samples are re-weighed after heating and the reduction in mass used to calculate organic matter content.

Soil microbial biomass was determined from a single 20 mm diameter core taken to the same depth as the density and water content cores. Samples were processed according to British Standard BS 7755: Section 4.4.2:1997 (which is identical to ISO 14240-2:1997). Soil microbial biomass is the mass of intact microbial cells in a given sample estimated from the carbon content of these cells. Fumigation with chloroform causes the cells to lyse releasing the matter contained within. Non-living organic matter is not seriously affected by such fumigation. The organic carbon is extracted by 0.5 M potassium sulphate solution from fumigated and unfumigated samples and the increase used to calculate microbial biomass carbon.

All statistical analysis was calculated using Statistica 10 (Statsoft Inc., Tulsa, USA) using a mixture of repeated-measures ANOVA and main effects ANOVA where appropriate.

Weather data was kindly supplied by M. Richards, from a monitoring station in Clifton, Bedfordshire approximately 5.5 miles from trial plots. The potential soil water deficit was calculated using WaSim (Cranfield University, UK).

7.3.2 Results

7.3.2.1 Density and water content

7.3.2.1.1 Density

Results were analysed using repeated-measures ANOVA, the repeating measure was time. Categorical predictors were soil type, depth and treatment. The strong influence of seasonal weather patterns and differences between the soils are the most prevalent effects, seen in every treatment for both soils. Soil O has on average a greater bulk density than Soil K, 1.43 ± 0.01 g cm^{-3} and 1.39 ± 0.01 g cm^{-3} respectively and the difference is clearly visible across all treatments (Figure 7.20).

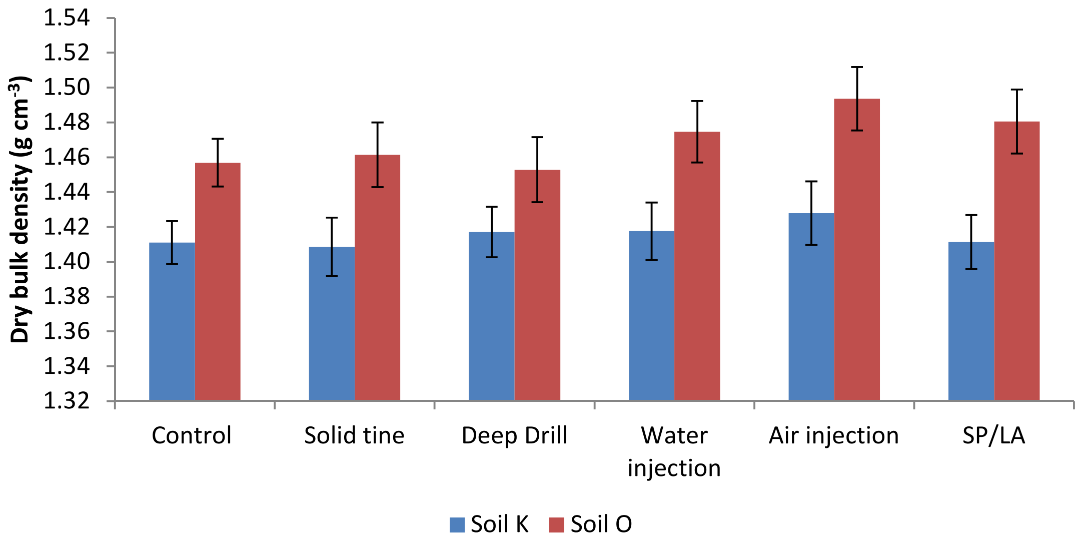


Figure 7.20 Mean dry bulk density over time for all treatments in Soil O and Soil K. Vertical bars denote standard error. Note vertical axis begins at 1.32 g cm^{-3} in order to maximise scale to highlight differences.

Dry bulk density peaks in June-October 2010 (Figure 7.21) due to an intensely hot and dry period which caused soil water to drop lower than previously at greater depths in the profile (Section 7.3.2.1.2) causing increased soil shrinkage and a consequently higher bulk density (Section 4).

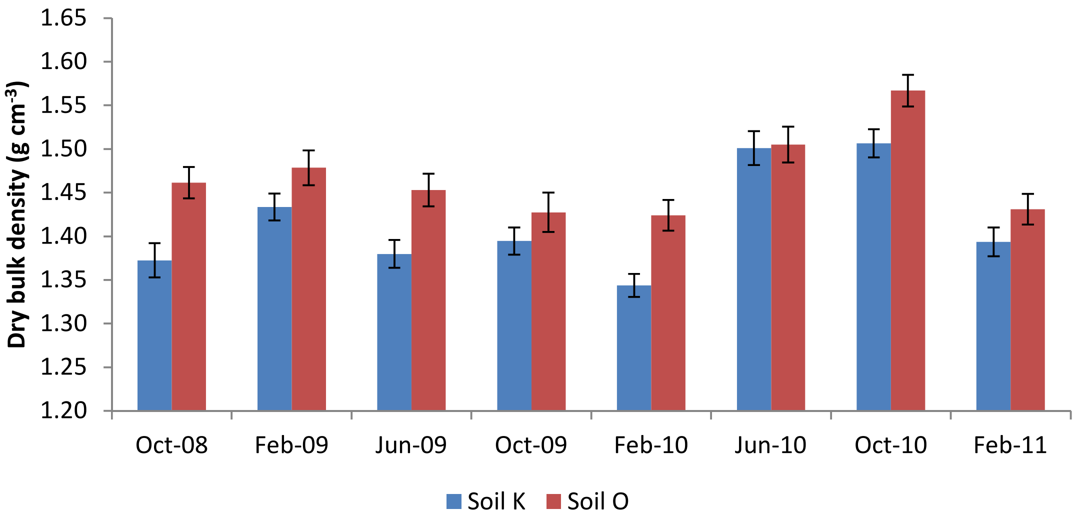
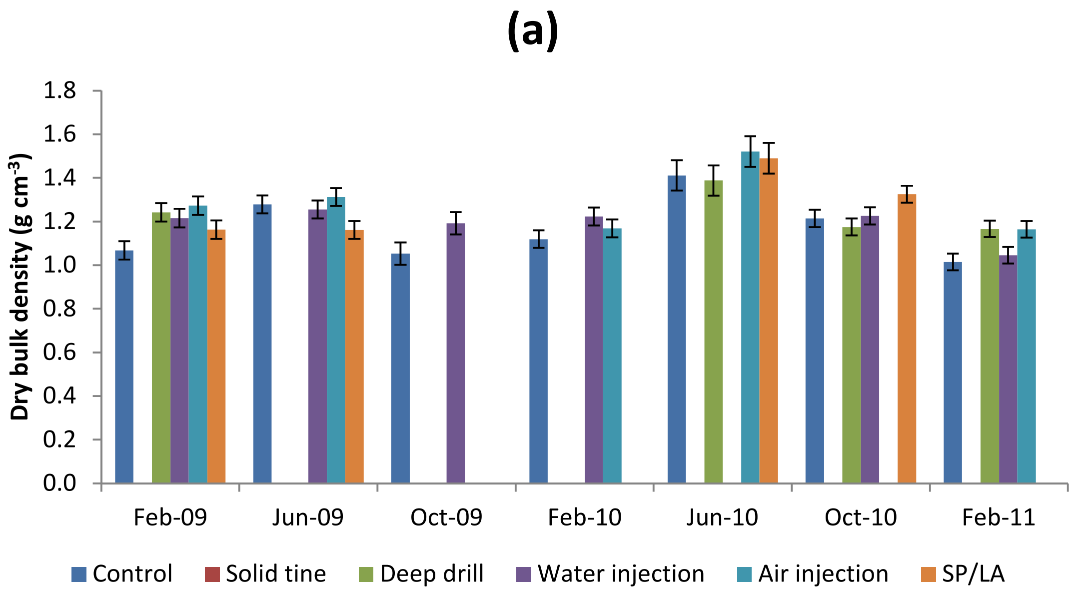


Figure 7.21 Mean dry bulk density across all treatments and over all depths for Soil K and Soil O at each time point. Vertical bars denote standard error.

Whilst the aeration treatments showed no significant effect irrespective of time there was a significant time*aeration treatment*depth interaction indicating that whilst the two soils show different densities the behaviour of the two soils over time with respect to aeration treatments is the same.

Most treatment effects are manifest in soil above 75 mm (Figure 7.22) which incorporates the maximum working depth of all of treatments bar the Water Injection and Deep Drill. Most of the treatment effects show increased bulk density. The Deep Drill is notable in that it shows an equal number of increases and reductions of bulk density over time; the mean of the increases is 0.11 g cm^{-3} and the reduction 0.05 g cm^{-3} so overall there is a general trend of increasing bulk density for all treatments in this range.



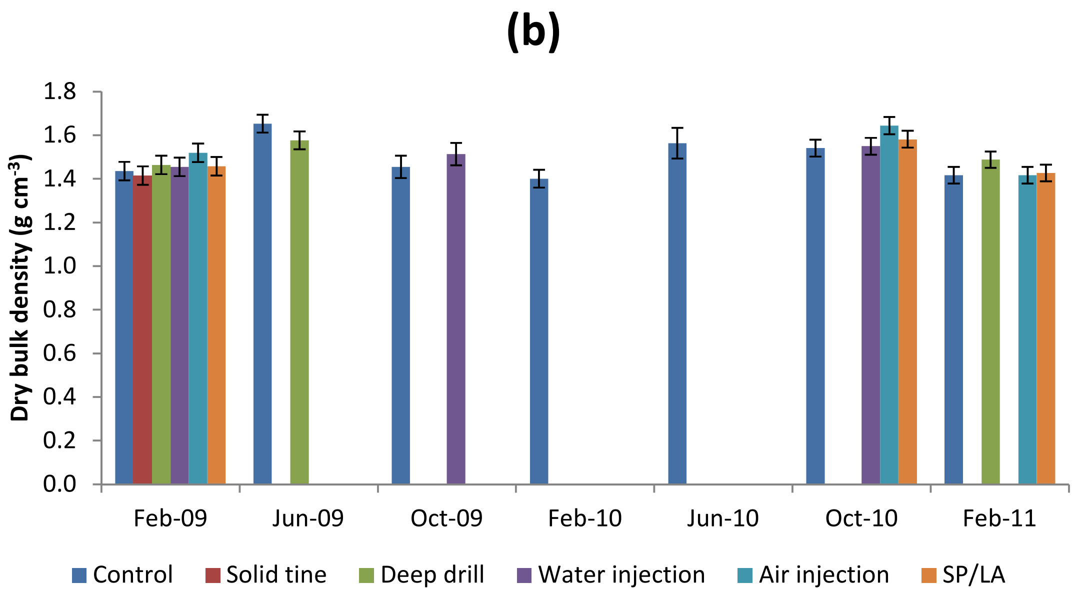


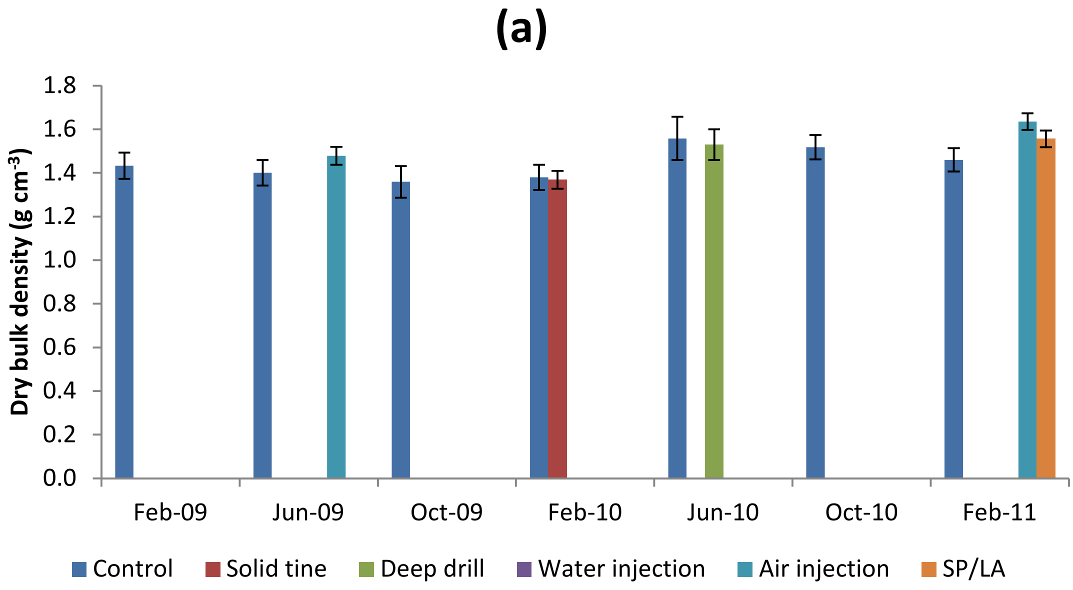
Figure 7.22 Dry bulk density over time averaged over Soil O and Soil K at depth 0-25 mm (a) and 25-75 mm (b). Treatments are only shown when they differ significantly from the control at p<0.05. Vertical bars denote standard error.

Between 75 mm and 125 mm depth aeration effects become much fewer with only five over the whole range two of which are barely perceptible decreases in density in Solid Tine and Deep Drill in February 2010 and June 2010 respectively. Of the remaining three, two are small but the Air Injection does cause a considerable rise in density in February 2011. Below 125 mm there are

12 more aeration effects, in a ratio of 1:3 reduction:increases in bulk density (Figure 7.23).

Air Injection and Water injection consistently increase bulk density particularly above 75 mm but also below. The Deep Drill shows an equal number of bulk density decreases and increases throughout the profile but the relative size of the increases is much larger than the decreases by a factor of approximately two. The Solid Tine shows two very small decreases in bulk density but is generally ineffective. In the single year of study the Spiked Roller showed both an increase in February 2009 and a decrease in June 2009. The Linear Aerator only increased bulk density except for June 2010 (and February 2010 but the difference was <0.01 g cm^{-3}) at depths below 125 mm.

In summary, aeration effects are consistent only in that the majority cause an increase in dry bulk density compared to the control, particularly Air Injection and Water Injection.



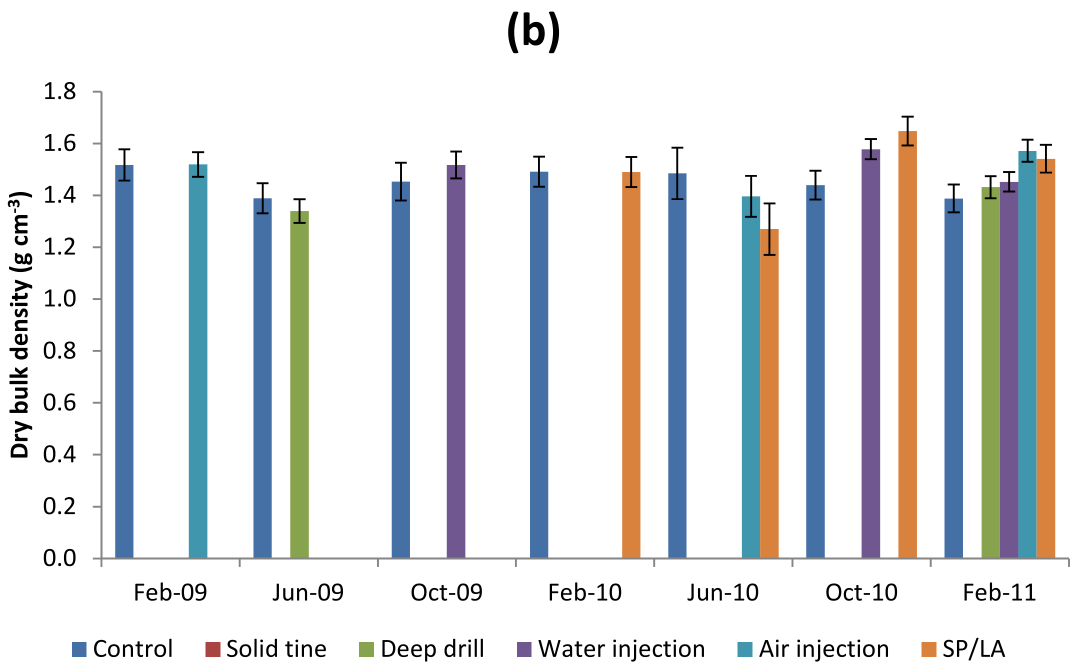


Figure 7.23 Dry bulk density over time averaged between Soil O and Soil K at depth 75-125 mm (a) and 125-200 mm (b). Treatments are only shown when they differ significantly from the control at $p<0.05$. Vertical bars denote standard error.

7.3.2.1.2 Water content

ANOVA analysis of the results from October 2008 showed only the depth as a significant factor on water content. Over time seasonal weather strongly influenced soil water content with minimum water content at all depths in June of each year. The uppermost layer of soil from 0-25 mm showed the greatest seasonal changes in water content. The top layer is most exposed to the weather and so consequently will show the greatest fluctuations with it. Soil below 25 mm showed some seasonal changes but less extreme than 0-25 mm (Figure 7.24) as the soil above it insulates it from surface conditions.

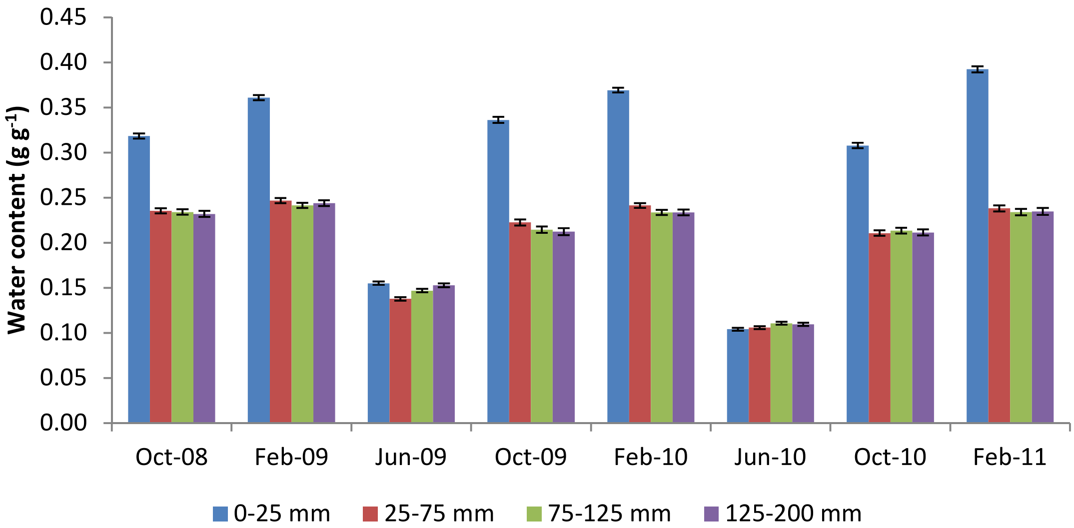


Figure 7.24 Water content averaged over all treatments at four depths over time. Vertical bars denote standard error.

The two soils also showed different behaviour over time. Soil O generally had a lower water content than Soil K, except in June of each year when Soil K had the lower water content which is surprising given the greater clay content and generally finer-texture of Soil O relative to Soil K.. The average difference between the soils was small though; 0.224 g g^{-1} in Soil O and 0.221 g g^{-1} in Soil K.

There was a significant aeration treatment effect irrespective of time, but only in Soil O. No aeration treatments in Soil K were significantly different from the control. In Soil O the control had greater water content than all other treatments. The Solid Tine, Air Injection and SP/LA treatments were significantly lower than the Deep Drill and Water Injection treatments which were the same as the treatments in Soil K (Figure 7.25). The total difference between the highest water content in Control in Soil O and the lowest water content in Air Injection in Soil O was 0.02 g g^{-1}, which may seem trifling but as observed in Section 5 even a small change in water content can drastically affect the gas diffusion capability of the soil.

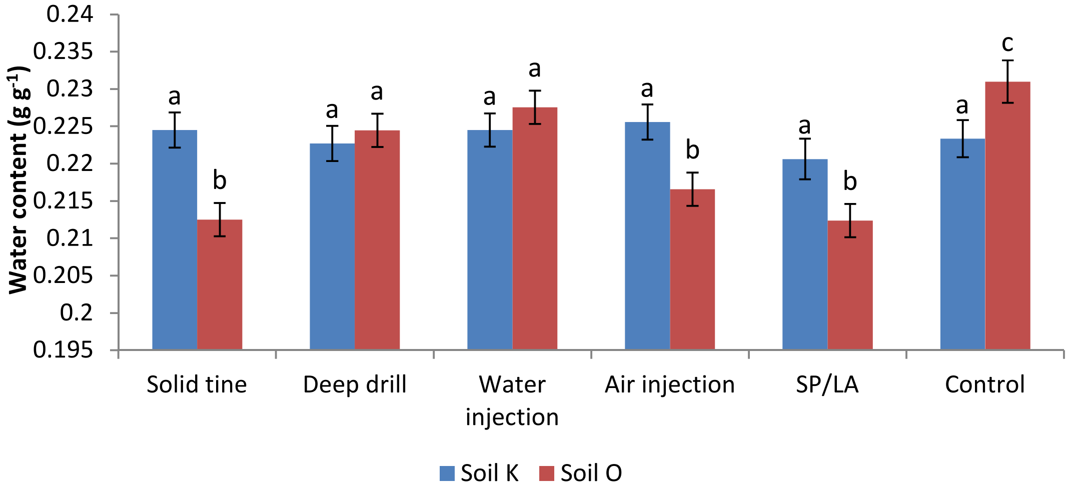


Figure 7.25 Water content averaged over time from Feb 2009 to February 2011 for each treatment. Letters indicate homogenous groups at p<0.05. Vertical bars denote standard error.

The highest order significant interaction was time*soil type*aeration treatment. As expected from the aeration*soil type interaction there are relatively few significant points where the aeration treatment differs from the control in Soil K (Figure 7.26).

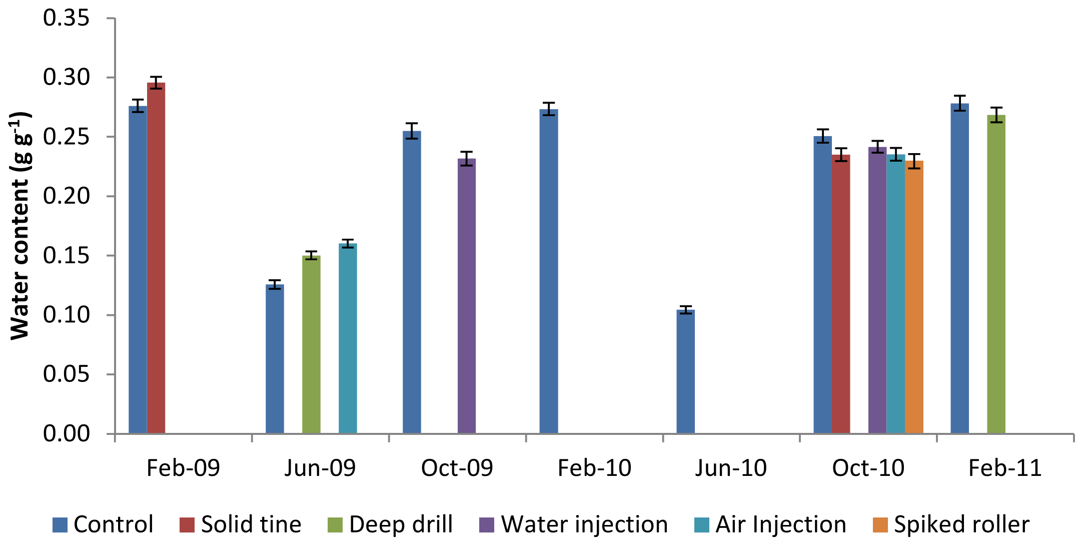


Figure 7.26 Mean water content of Soil K over all depths in the control. Treatment water contents are shown when significantly different from the control at p<0.05. Vertical bars denote standard error.

Most of the differences are concentrated in October 2010 which coincides with the density in October 2010 being abnormally high compared to the previous two years.

In Soil O there are many more effects than in Soil K (Figure 7.27) that echo the aeration treatment*soil type effects discussed earlier where the treatments all show decreased water content relative to the control, particularly the Spiked Roller, Linear Aerator, Solid Tine and Air Injection.

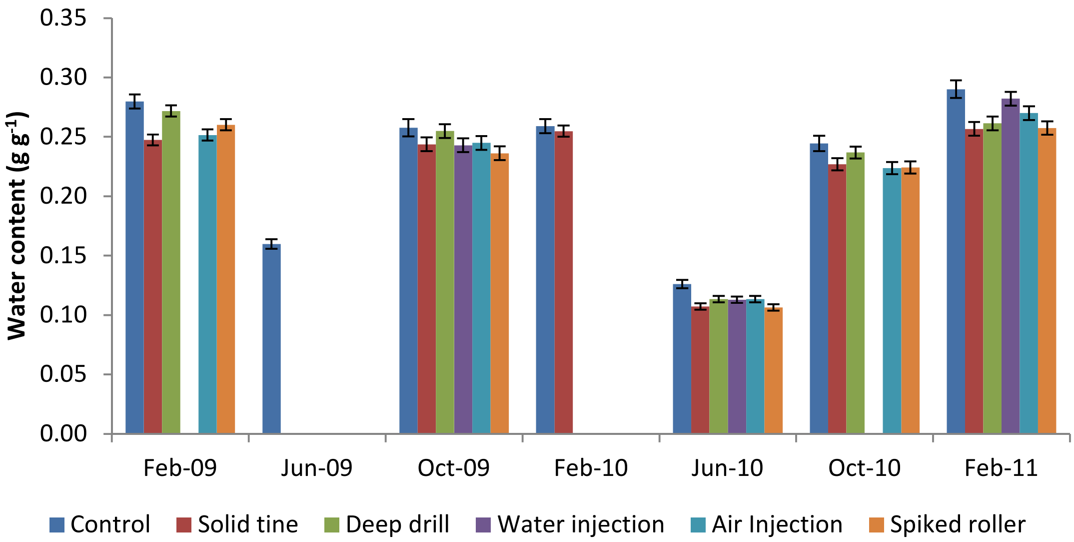


Figure 7.27 Mean water content of Soil O over all depths in the control. Treatment water contents are shown when significantly different from the control at p<0.05. Vertical bars denote standard error.

ANCOVA (Analysis of covariance) of density with time as a random factor, water content as a continuous predictor and categorical predictors of soil type, depth and treatment revealed that water content was not significant at $p<0.05$ in affecting density. The link between water content and bulk density is generally closely linked (Section 4) however, frequent rolling during the spring may have counteracted the usually closely linked correlation in this case.

7.3.2.2 Surface hardness and penetration resistance

7.3.2.2.1 Surface hardness

Main effects ANOVA of October 2008 measurements taken prior to any treatment showed the only significant differences were between soil types.

The results were analysed using repeated-measures ANOVA, the repeating measure being time. Surface hardness (SH) revealed a significant aeration*soil type interaction (Figure 7.28). Air Injection and Solid Tine lowered SH relative to the control in Soil K. SH in Soil O was elevated across all aeration treatments relative to control except SP/LA. There were no other significant interactions involving aeration treatments.

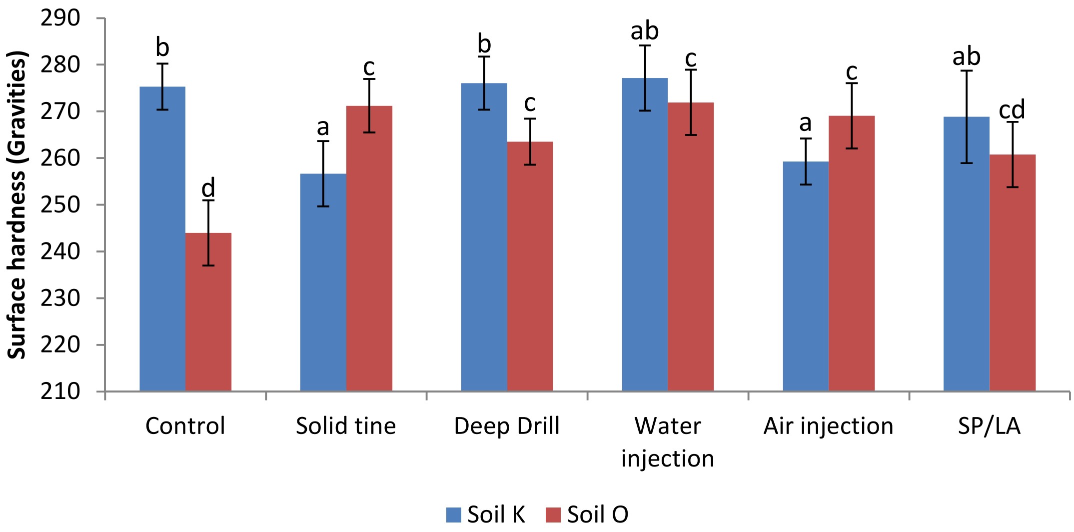


Figure 7.28 Mean surface hardness over time for each treatment in Soil O and Soil K. Letters represent homogenous groups within each soil type. Vertical bars denote standard error.

Over time the two soils follow the same general pattern of behaviour and at time points outside of June each year are not significantly different from each other. February 2009, 2010 and 2011 are not significantly different from each other, nor are October 2009 and 2010. June 2009 and June 2010 are significantly different from each other and also show a significant difference between the two soils at these times (Figure 7.29).

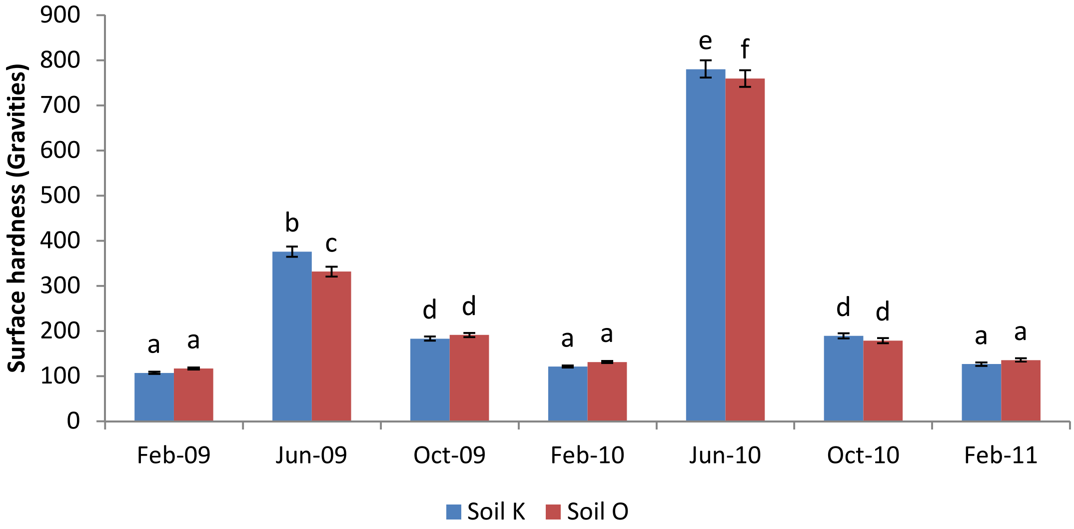


Figure 7.29 Mean surface hardness over all treatments for each time point in Soil O and Soil K. Letters indicate homogenous groups ($p<0.05$). Vertical bars denote standard error.

7.3.2.2.2 Penetration resistance

7.3.2.2.2.1 Energy required to penetrate

Only soil type and time were significant in affecting the energy required to penetrate the soil (ERP). Values for each soil were: Soil O 27.5 ± 0.5 J, Soil K 25.5 ± 0.5 J.

Over time there was a general trend of increased ERP in October of each year relative to February which corresponds to the relative water contents at these times where the drier Octobers have greater penetration resistance.

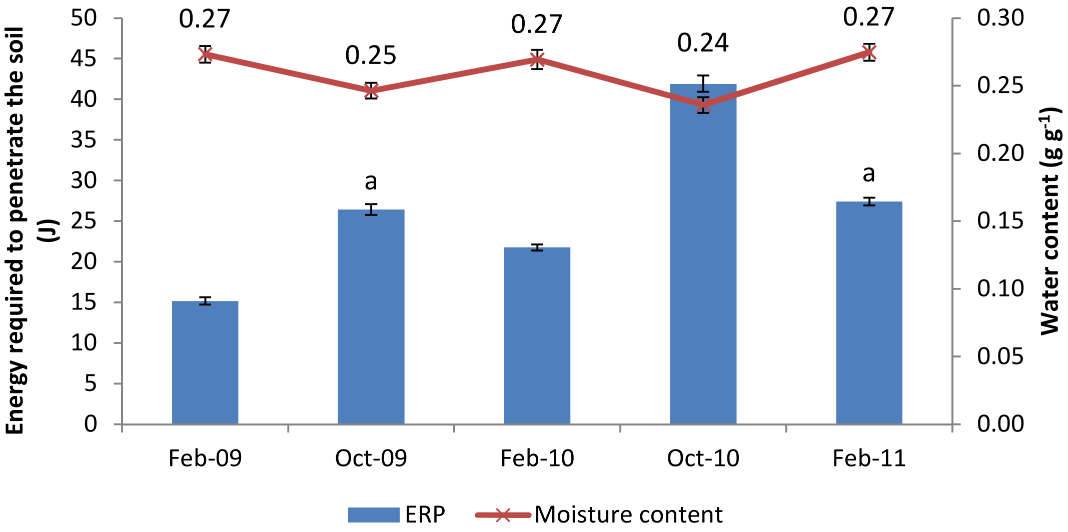


Figure 7.30 Mean energy required to penetrate the soil over all treatments and soils for each time point and the corresponding mean water content over all depths and treatments. Letters indicate homogenous groups within each soil type ($p<0.05$). Vertical bars denote standard error.

7.3.2.2.2.2 Depth and magnitude of maximum resistance to penetration

This parameter is primarily aimed at finding out if a compacted layer of soil is being created by treatments. If such a layer was to form it would be expected to show the greatest maximum resistance as if another area of soil is more dense due to other factors (i.e. rolling) it is likely that the compaction caused by the aeration treatment is of less concern.

Air Injection caused an increase in the depth of maximum resistance compared to the control in Soil K, all other treatments did not significantly alter the depth of maximum resistance. An increase in the depth of maximum resistance would indicate a soil loosening effect from treatment. The Deep Drill, Water Injection and Air Injection showed differences between soil types (Figure 7.31) but were not significantly different from the controls in each soil.

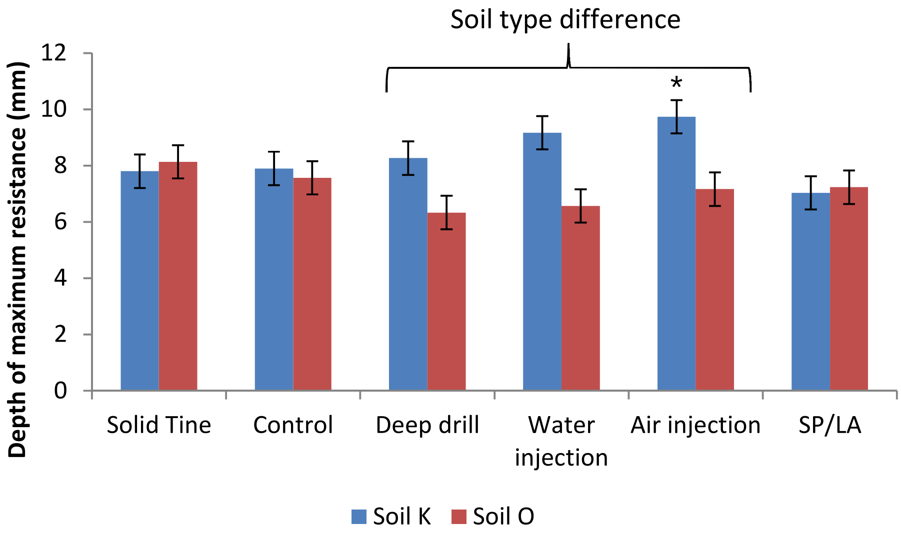


Figure 7.31 Depth of maximum resistance for each treatment and each soil averaged over time. ✱ indicates significant difference from the control (p<0.05).

Soil K generally had a greater depth of maximum resistance than Soil O which was present in October 2008 through to February 2011 and was taken as an intrinsic property of the soil and general maintenance regime. The depth of maximum resistance was generally near the surface at a depth of 8 ± 2 mm created by the rolling of the pitch during the summer months. The maximum resistance to penetration shows a similar divergence between soils (Table 7.11).

Table 7.11 Mean depth of maximum resistance and mean magnitude of maximum resistance over all time points and over all treatments in Soil O and Soil K.

	Depth (mm)		Magnitude (MPa)	
	Mean	St Error	Mean	St Error
Soil K	8.32	0.24	1.73	0.04
Soil O	7.17	0.24	1.88	0.04

Once again the only significant deviation from the control is in Air Injection in Soil K which shows a reduction in the magnitude of the maximum resistance to penetration (Figure 7.32). The combination of an increase in the depth of maximum resistance and a decrease in the magnitude of maximum resistance possibly indicates that a layer of compacted soil has been broken down by the treatment.

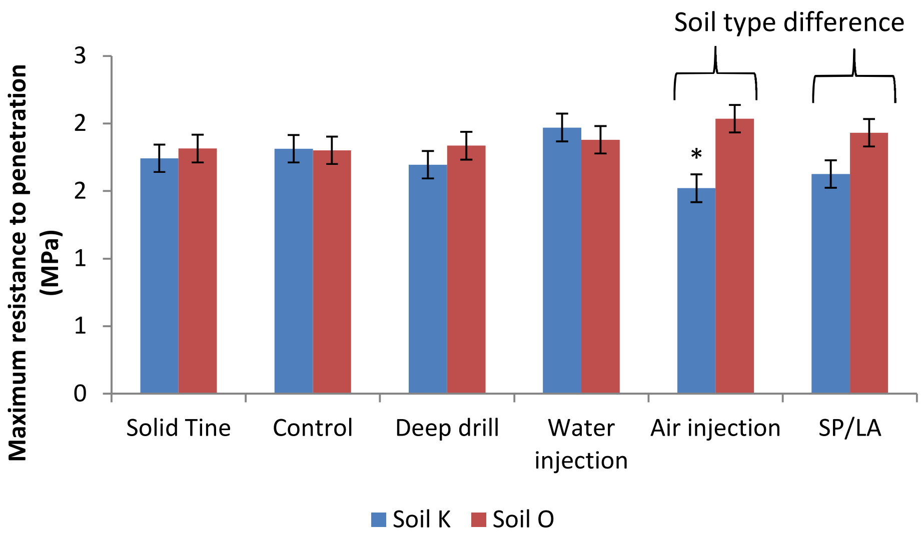


Figure 7.32 Mean maximum resistance to penetration over time for each treatment in Soil O and Soil K. ∗ indicates significant difference from the control ($p<0.05$).

7.3.2.3 Organic matter content and microbial biomass

7.3.2.3.1 Microbial Biomass

Repeated measures ANOVA of the data reveal a strong soil type dependency on microbial biomass. Soil K (mean 147 ± 6 µg g^{-1}) had a consistently smaller size of microbial community than Soil O (mean 211 ±7 µg g^{-1}). The variation of the two soils with time is very similar and the time*soil type interaction was not significant. The microbial population starts at a low level in October 2008 through to February 2009 compared to June 2009, where it peaks, before coming to a medium value between the initial low and the peak in June where it remains fairly constant (Figure 7.33).

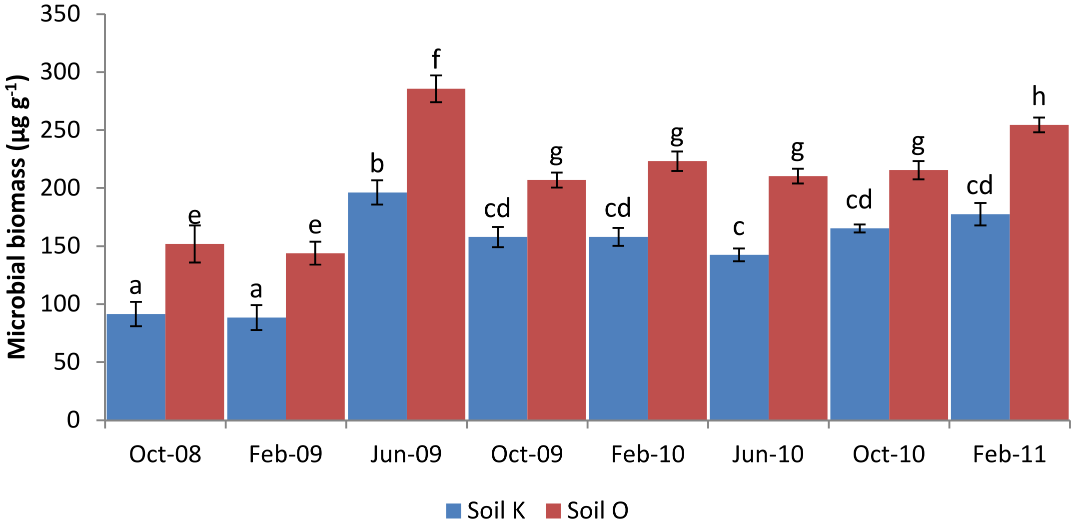


Figure 7.33 Average microbial biomass across all treatments in Soil O and Soil K for all time periods. Letters indicate homogenous groups at $p<0.05$. Vertical bars denote standard error.

In Soil O no treatments were different from the control. In Soil K only Water Injection differed from the control (162 ± 4 µg g^{-1}) in that it slightly lowered the microbial population to (140 ± 4 µg g^{-1}). There were no significant higher order interactions.

7.3.2.3.2 Organic Matter

The organic matter content also showed a strong separation by soil type. Soil K consistently showed a significantly higher organic matter content than Soil O. The average organic matter content in Soil K was 5.7 ± 0.02 % and in Soil O 4.5 ± 0.02 %. The time*soil type or soil type*treatment interactions were not significant so despite the overall difference in organic matter content the behaviour was not different in either soil over time or treatments.

The behaviour over time follows a seasonal cyclic pattern (Figure 7.34). Organic matter content peaks in February of each year and is minimised in October of each year. The initial organic matter content is high in 2008 but declines rapidly in 2009. The cycle from year to year from then on remains broadly constant.

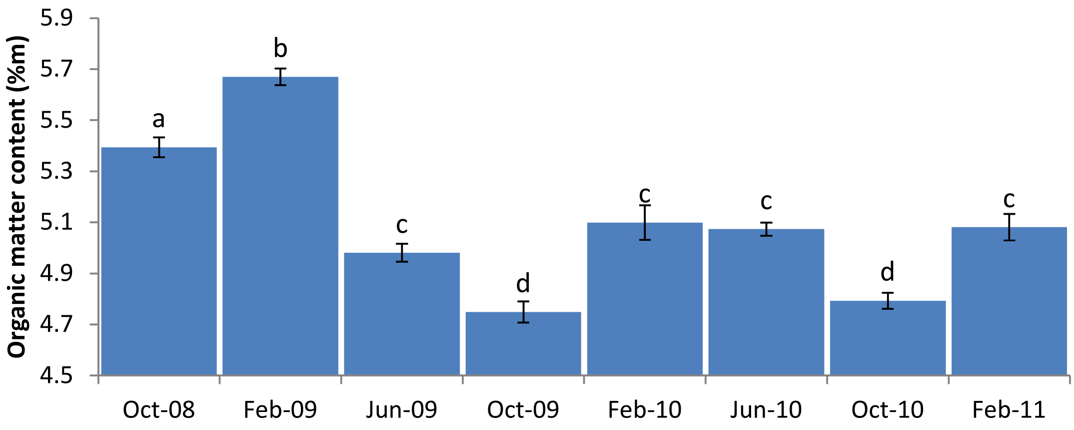


Figure 7.34 Mean organic matter content of both soils for all treatments over time. Letters indicate homogenous groups at p<0.05. Vertical bars denote standard error.

The behaviour at different layers in the soil profile did not vary for treatment or time but like soil type there was a significant difference between layers overall as the average organic matter content in the top 25 mm of soil was much greater than subsequent depths (Figure 7.35)

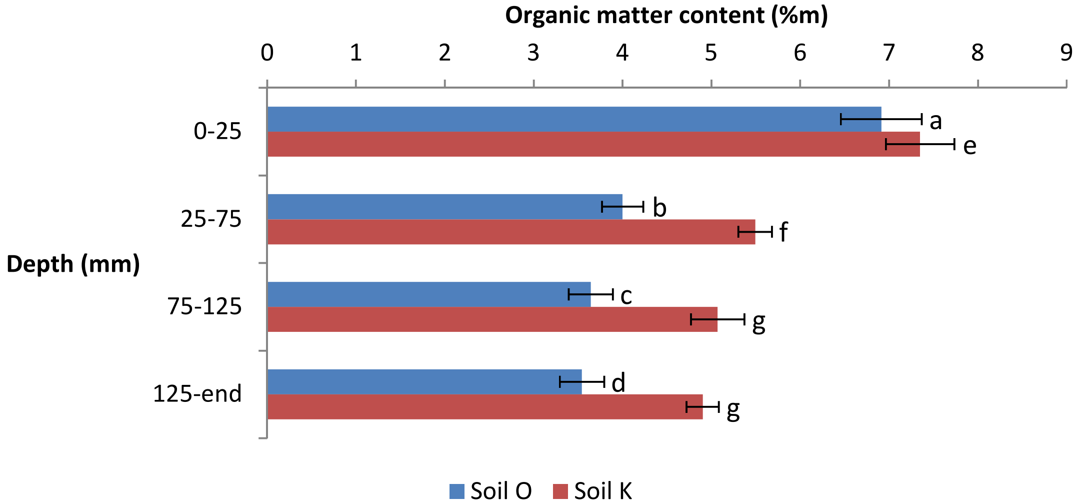


Figure 7.35 Mean organic matter content across all treatments, time at for defined depths for Soil O and Soil K. Letters indicate homogenous groups at p<0.05. Vertical bars denote standard error.

There were no significant time*aeration treatment effects. Only in the top 0-25 mm were any aeration treatment effects observed, both the Air Injection and Solid Tine showed reduced organic matter content relative to the control, however the behaviour of the treatments over time did not vary from the control and examination of the area in October 2008, before any treatment, revealed the same pattern of reduced organic matter (Figure 7.36), so this is not a treatment effect but a pre-existing condition of the test area.

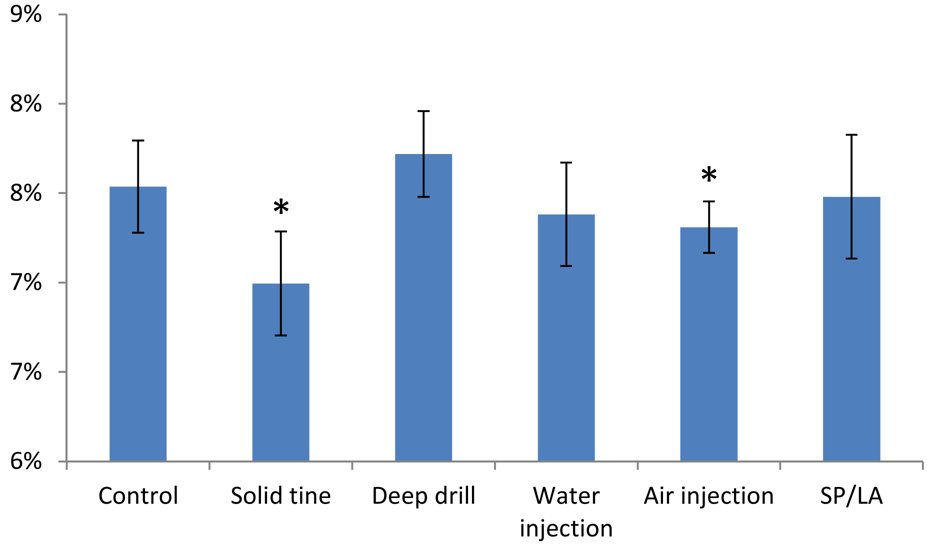


Figure 7.36 Mean organic matter content over Soil K and Soil O across each treatment area in October 2008 prior to treatment application. Vertical bars denote standard error. Star indicates significant difference from the control.

7.3.2.3.3 Microbial populations and other factors

The results were analysed using ANCOVA in Statistica 10 (Statsoft, USA). Time was modelled as a random variable, while organic matter, density and water content were continuous predictor variables. Due to the large divergence in microbial population size and organic matter content between soils they were examined individually. In both soils the effect of organic matter, density and water content on microbial biomass was not significant at $p<0.05$.

7.3.3 Discussion

Murphy *et al.* (1993) found that solid tine cultivation did not affect soil bulk density in a loamy sand over the course of a year. Murphy and Rieke (1994) found that water injection decreased soil bulk density in a loamy sand over a year compared to solid tines but not compared to the control. No other results were found in the review of the literature despite numerous claims that the primary aim of aeration is to reduce bulk density. Several studies measured penetration resistance as an indicator of aeration effectiveness in sandy soils generally reporting a short-lived effect of between 1-10 weeks of reduced penetration resistance from solid tine aeration (Guertal *et al.*, 2003; Murphy *et al.*, 1993; Morhard and Kleisinger, 2004; Prämaßing *et al.*, 2009).

Both water content and density show clear seasonal trends in their behaviour over each year. In the summer both soils show a minimum in water content and a maximum in bulk density. This trend is generally true throughout the soil profile although deeper layers often exhibit a lag in behaviour compared to shallower regions as the above soil insulates the deeper regions from surface variations. The seasonal variation in bulk density and water content is much greater than any observed treatment effects.

The differences between the two soils in soil bulk density and water content, whilst significant, are small. The bulk density of the two soils showed the same patterns of behaviour over time, but the water content showed significantly different behaviour over time between soils. The bulk density showed variation between layers over time whereas water content did not. Water content and dry bulk density in unconfined shrink-swell soils in the laboratory are closely linked (Section Shrink-Swell). Dry bulk density in the field however depends on a number of other factors including rolling regime, grass roots (restricting crack formation by increasing soil strength (Adams *et al.*, 1985), soil structure, depth/overburden and finally the weather: not just the action of rain to increase water content but the rate at which water is lost, the balance between gain and loss and also the action of freezing and thawing to reduce bulk density. The potential soil water deficit over the period of the experiment is shown in Figure

7.37; every year there is a clear general pattern of a deficit build-up over the summer months which is reduced to zero within December of each year. Considerable variation exists between each year as to the rate at which the deficit is built and reduced each year, particularly the recovery in 2009 relative to 2010. 2010 showed a gradual reduction in the magnitude of the deficit from August to December, whereas 2009 showed little reduction in deficit until November after which it rapidly reduced to zero.

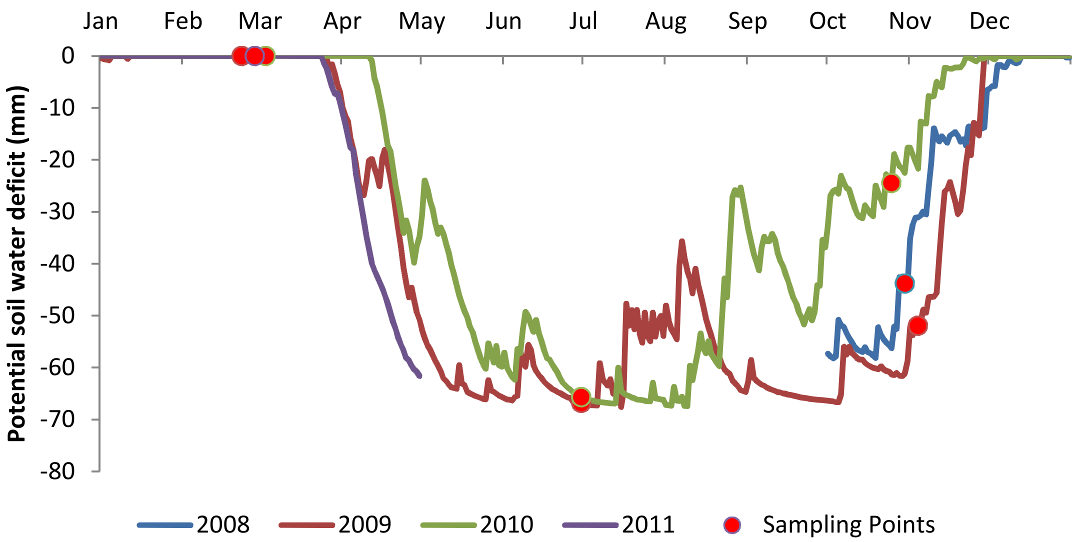


Figure 7.37 Potential soil water deficit from 1st October 2008 to 30th April 2011 showing repeated measures sampling points.

As demonstrated in Section 4 the behaviour of the soil is a dynamic process of which only snapshots are taken here yet it is the product of factors over time that influence bulk density, soil strength and water content which must be considered when analysing the results.

Density changes from aeration were mostly observed above 75 mm depth. Murphy and Rieke (1994) found for hollow tining and water injection that density effects from treatment were only observed above 76 mm depth in a loamy sand. The working depth of all aeration treatments bar Deep Drill and Water Injection were to 75 mm so most effects would be expected in this zone particularly as it has the least overburden compared to deeper layers in the profile allowing less restricted shrink-swell. The working depth of the Water Injection machine in a clay soil is unknown. In sandy soils it has been reported as 100-200 mm (Gibbs *et al.*, 2001). It would be expected in the finer textured soil that the working depth of the Water Injection would be reduced due to the restrictions that pore size places on flow rates (Gäth and Frede, 1995a) and so will be less than 100 mm.

7.3.3.1 Aeration does not decrease dry bulk density

The aeration treatments generally had no effect or actually increased bulk density. The Solid Tine had no effect, Air Injection and Water Injection generally increased density, and the Spiked Roller and Linear Aerator showed some increases and some decreases giving an overall net neutral effect with time. On the basis of this the hypothesis that aeration will decrease bulk density by creating extra pore space must be rejected. The opposite effect is observed that in general there is an increase in soil bulk density from aeration treatment. For treatments that do not involve the removal of soil from the soil, Solid Tine, Water Injection, Air Injection and Spiked Roller the obvious explanation is that when sampling between tine holes a net increase in compaction will be observed as the treatments are merely a rearrangement of pore space creating large macropores at the expense of smaller pores (Murphy *et al.*, 1993) so when sampling between the new large artificial macropores a general increase in density is expected as the relative volume of the soil is unchanged. The Deep Drill physically relocates soil upwards through the profile to the surface thereby decreasing the mass of soil within, which should reduce density. Point measurements between tine holes throughout the year showed an equal number of reductions and increases from treatment. Clearly the overall reduction in soil bulk density is not large enough to be detected. Given the total volume that is affected by the aeration treatments this is not surprising (Table 7.12) as only 0.6% of the soil is removed by a single application of the Deep Drill treatment which corresponds to a reduction in bulk density of 0.008 g cm^{-3}.

Table 7.12 Volume of artificial macropores created by the actions of the aeration treatments relative to the total volume of the soil (to 200 mm) and the accompanying increase in surface area.

Treatment	Tine hole volume relative to total volume	Increase in surface area
Air injection	1.8%	141.4%
Solid Tine	0.8%	90.0%
Deep Drill	0.6%	51.9%
Linear Aerator	1.1%	20.5%
Spiked Roller	0.3%	52.4%

Linear Aeration also involves removal of the soil from the profile but is limited to the top 20 mm. This treatment saw a general increase in bulk density and no particular effect in 0-25 mm layer of soil. The relatively small amount of soil removed and the limited depth mean that as a method of bulk density reduction this machine overall fails possibly because of the fact that it is tractor mounted and therefore heavy and compressive. The primary aim of the treatment though is thatch removal unlike the other treatments therefore its behaviour in this regard is not surprising.

7.3.3.2 Aeration will increase bulk density at its working depth due to compaction of the soil (except deep drill).

The bulk density of the soil at any depth in the soil was not consistently increased due to any aeration treatment. Possibly the measurements of bulk density were not sufficiently sensitive enough to capture this or it did not occur. Given the low volume of soil directly affected by each treatment even if the compaction effects were not ameliorated from each year and between applications the maximum cumulative affected volume is only 10.8% (from two applications of Air Injection each year) so any detectable effect will be small. Potentially a much longer time period of repeated application may be required to see a compaction pan develop.

The depth of maximum resistance as measured by the penetrometer is further evidence that no compaction from aeration was observed. The only treatment effect was in Soil K from Air Injection which resulted in a reduced magnitude of maximum resistance and a greater depth of maximum resistance. The combination of the two changes would indicate that a layer of soil previously representing the greatest resistance to penetration has been ameliorated so that the new layer of maximum resistance is now another layer in the profile at a different depth, in this case deeper in the profile. This effect was also visible in Section 7.2 and is evidence that aeration can have long term effects on soil properties. The Air Injection treatment was the only one to demonstrate this; the remaining treatments did not show a change from the control. That the Solid Tine treatment did not show a similar effect would indicate that this was due to the compressed air addition to the Air Injection process. This once again highlights the difference in response of the two soils to the injection of compressed air. In Section 7.2 Soil K showed no difference in ERP and MRP between the effects of Solid Tine and Air Injection treatments, but Soil O did; whereas in the long term data there seems to be no effect in Soil O but a significant effect in Soil K. Both the immediate effects of ERP and MRP in both soils have gone by February of each year, however the change in DMR in Soil K remains. Soil K has a much greater proportion of large pores than Soil O (Figure 7.38), flow through smaller pores requires a much higher pressure than flow through larger pores to achieve the same rate according to the Hagen-Poiseuille equation for compressible fluids (7.2)

$$\Phi = \frac{\pi R^4}{16\eta L}\left(\frac{P_i^2 - P_o^2}{P_o}\right) \qquad \textbf{(7.2)}$$

Where Φ is the volumetric flow rate, P_i is the inlet pressure, P_o is the outlet pressure, L is the length of the tube, R is the radius of the tube and η is the viscosity of the fluid.

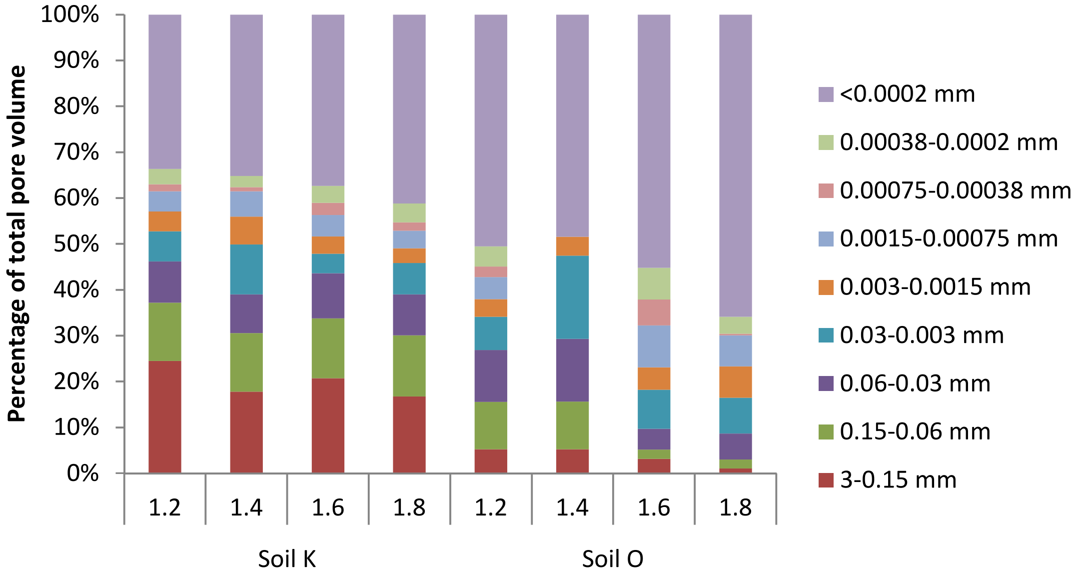


Figure 7.38 Pore size distribution of Soil K and Soil O at four different densities. Pore sizes and relative volumes were calculated from water release curves in Shipton (2008) using the method from Marshall *et al.* (1996). The graph was designed to illustrate the proportional changes in pore size distribution with increasing bulk density.

Therefore if all other factors remain constant save for R and L, the radius of soil effected by the compressed air is L which is proportional to R^4 so even a small change in average pore size will drastically effect the radius of effect. Consequently when the air is thrust into the tine hole the force is contained in Soil O in a more confined space due to the smaller pores resulting in a greater force but over a smaller area. In Soil K with larger pores the air can flow more readily and the force is dissipated over a wider area. Bulk density is obviously linked to this as it directly affects the distribution of pore sizes (Figure 7.38). It is believed that the difference in density through the profile between the years is the cause of the changing effectiveness of the different aeration treatments and the cause of the differences between Soil O and Soil K in ERP and MRP in the immediate effects of aeration. The density of Soil K in 2010 and Soil O in 2008 are similar and show similar positive trends in ERP and MRP. Whereas the low density Soil K in 2009 and high density Soil K in 2010 show negative trends in ERP and MRP from treatment perhaps indicating an optimum of bulk density

(>1.39 g cm^{-3} but <1.56 g cm^{-3}) and hence pore size for each soil where the action of the compressed air is most effective.

Overall in summary the data leads to a rejection of the hypothesis that repeated aeration treatments to the same working depth will cause a compacted layer of soil to be rejected for the time period studied. Potentially over a longer period this may yet be demonstrated.

7.3.3.3 Aeration will decrease water content due to increased surface area and increased hydraulic conductivity

This hypothesis is supported only in Soil O despite the large increases in surface area created by aeration treatment in each soil (Table 7.12). Soil K showed no consistent effect of treatment on water content. There were a few time*treatment*soil type effects in Soil K where the treatments differed from the control mainly in October 2010. In contrast in Soil O numerous effects were seen at each time point and for each treatment. Figure 7.38 shows the pore size distributions of the two soils measured over a range of densities. The two soils differ at opposite ends of the pore distribution. Soil O has a much larger proportion of fine pores than Soil K, whereas Soil K has a much larger proportion of larger pores relative to Soil O. One possibility for the ineffectiveness of aeration in reducing soil water content in Soil K could be that the pore size distribution having a larger proportion of larger pores is already effective at reducing water and the addition of artificial macropores has no effect. Shipton (2008) showed that Soil K had a greater rate of evapotranspiration than Soil O in a pot experiment which was believed to be related to the pore size distribution. Soil O which has a much lower proportion of large pores is affected much more strongly by the addition of large macropores which increase the efficiency of water removal more greatly than the existing network more narrow pores.

It has been postulated that tine holes could increase water capture and storage in the soil by acting as small reservoirs capturing surface run-off. Cattle (1999) found in the hot Australian climate that solid tined soil increased evaporation due to the enlarged surface area which outstripped any gains from increased water capture. Cattle (1999) hypothesised in a cooler climate the reduced level of evaporation would show a net gain in water storage in the soil. The results of this experiment concur with the findings in Australia that increased evaporation from treatment outstrips gains in water capture. The reduced water content due to treatment is potentially more beneficial than water capture as Autumn-Winter too much water is generally more of a problem than too little and even a small reduction in water content can have a profound effect on the movement of gases through the soil (Section 5).

The reason for the concentration of treatment effects in Soil K in October 2010 could be due to the weather that year that showed reduced evapotranspiration relative to rainfall resulting in a steady decrease in magnitude of the soil potential water deficit (Figure 7.37) in contrast to the rapid decreases seen in 2009 and 2008 generally occurring later in the year. Potentially the gradual addition of water to the profile earlier in the year when average temperatures are warmer gave greater opportunity for increased evaporation from the aerated soils, due to the higher surface area, to create a significant difference in water content from the control.

7.3.3.4 Surface hardness

The high dependence of SH on water content is apparent in the data with clear seasonal trends in SH in line with the water content. SH is lowest in February of each year, and peaks in June each year following the inverse trend of water content. The difference in SH between the treatments and controls in Soil O are similarly water related as the treatments resulted in reduced water content.

In Soil K, Air Injection and Solid Tines produced a small reduction in SH that was not reflected by increased water content in those treatments.

The Solid Tine and Air Injection methods are very similar in their mode of penetrating the soil essentially being the same machine, one with the addition of air injection. As such, similar effects may be expected particularly if those effects relate to just the action of the tines on the soil. It cannot be determined from the evidence presented here by which mechanism the reduction in surface hardness is caused by. The collection of density cores involves driving the soil corer into the ground using repeated blows from a mallet. The act of penetrating the soil with the corer will cause a certain amount of compaction to the soil particularly nearer the surface. The reduction in surface hardness could then indicate a slight decompaction effect from the solid tine and air injection techniques that was not detected in the bulk density data.

7.3.3.5 Organic matter content and microbial biomass

The general values found are low, Bartlett *et al.* (2008) found on a golf course fairway of a similar soil type biomass levels between 400-800 µg g^{-1}. Bartlett *et al.* (2008) found as management intensity increased microbial biomass decreased such that the most intensively managed tee and green areas showed significantly smaller microbial biomass (300-400 µg g^{-1}) than the less intensively managed rough and fairway areas (c. 700 µg g^{-1}). The values for the tee and green are still substantially higher than those found in the test area demonstrating the effect of the compacted soil in reducing microbial biomass. It is difficult to compare directly between surveys as the test is sensitive to the particular user running the test, as well as the numerous differences between the two sample sites in terms of management and grass species so only limited conclusions can be drawn from this (Pawlett, 2012; Ritz, 2012).

Tests of the grassland immediately surrounding the test area showed levels of 1000-1200 µg g^{-1}. The difference is primarily down to the level of disturbance and carbon inputs into the soil. On the grassland surrounding the test area the soil is not compressed by annual rolling and the clippings are returned to the surface providing an input of carbon into the soil system. On the test area grass clipping were removed and the surface regularly scarified to remove surface organic matter build up. Together with the compaction of the soil (Section 2) this resulted in much smaller microbial biomass. Only very limited use was made of pesticides, restricted to herbicides for the control of dicotyledon weeds, applied annually each spring. This may have negatively affected the microbial population, however, it would be expected that following the application there would be a significant drop in microbial biomass but this was not observed in the data.

7.3.3.5.1 *Aeration does not increase microbial biomass due to increased oxygenation and consequently does not reduce organic matter*

There were no significant effects of aeration treatments on organic matter content and only the Water Injection treatment significantly altered the microbial population by reducing it relative to the control. Generally the time and soil type significantly affected both microbial biomass and organic matter.

Soil O had a greater microbial biomass but lower organic matter content relative to Soil K. ANCOVA analysis showed that there was no significant relationship between the microbial biomass and organic matter content seemingly indicating that the reduced level of organic matter in Soil O is not due to the increased microbrial population. Similarly ANCOVA analysis of water content and density showed no significant effects on the microbial population. Shipton (2008) found increased root mass in Soil K relative to Soil O in pot experiments which could explain the increased organic matter in this soil which was confirmed in the test area in Section 7.4. In Section 6 microbial biomass was found to follow the same trends as root density, therefore if increased root density is resulting in a higher level of organic matter a corresponding increase in microbial biomass would also be present but as this is a comparison between soils this relationship may be different from that observed for a single soil.

Despite an overall difference between the soils they show the same pattern of changes in microbial biomass over time. Microbial biomass peaks in June 2009 from an initial low in October 2008-February 2009 and then levels off at a slightly elevated level for the remaining time. This behaviour is irrespective of any treatment so is the result of factors affecting the whole trial area such as general management and weather. That the pattern shows an initial variation before settling to a steady state level would indicate that it is most likely consistent management of the pitches (the initial variation stemming from the adjustment of the system to the new management regime) rather than the weather which shows considerable year to year variation.

7.3.3.6 Increased microbial biomass will decrease organic matter.

Organic matter content shows a different cycle, starting from an initial high, it then peaks in February 2009 before declining to a cyclic steady state of an equal elevated level in February and June each year and reduced level in October of each year. Analysis of covariance revealed no significant linear relationship between microbial biomass and organic matter content. Once again a lack of treatment effect would indicate management (i.e. scarification, rolling, irrigation and topdressing that are done to every plot equally) are the root cause of the changes observed, in particular scarification the primary purpose of which is the removal of surface organic matter. There does seem to be a general link with microbial biomass which peaks in June 2009 corresponding to a large reduction in organic matter, biomass then remains at an elevated steady state and organic matter remains at a lowered steady state.

From this it would seem that increased microbial biomass does decrease soil organic matter content and is unaffected by aeration treatment.

7.3.3.7 Method limitations and future research suggestions

The broad focus of the work examining several treatment types meant a compromise on the examination of changing treatment application regimes. The trials were designed to mimic the application regimes currently used by the majority of groundsmen which results in a gap in the knowledge of how changing application regimes of the aeration treatments (e.g. changing the frequency of application, changing the start date and end date, changing the working depth, using different tine types) may alter the effectiveness of treatments.

The effects of aeration on the plant and soil microbes were only studied in a limited fashion. Microbial biomass gives an indication of population size but not composition. The community structure of the microbial populations would give a better indication of the health and activity of the microbes within the soil as discussed by Bartlett *et al.* (2008) for different areas of a UK golf course. Root density was examined at only one time point (Section 7.4) and would have provided a more informative view had it been studied over the entire time period to examine more closely the effect of aeration on rooting characteristics in the field. This was not done during the trial here due to time limitations; determining root density is very laborious and takes a considerable amount of time.

Whilst the pitches were designed to mimic a cricket pitch they have never had the wear and damage of a cricket game. Studying a fully operational cricket pitch would be beneficial however gaining access to one and maintaining the playability when taking multiple cores from the soil would be challenging and off-putting for any potential volunteer groundsmen.

7.3.4 Summary of key points in Long Term Data

The effect of seasonal weather patterns and general maintenance dominate all the variables measured. Where aeration is proven to have a significant effect this is often small in comparison.

Below 75 mm depth dry bulk density is generally unaffected by aeration treatment. Above 75 mm the effect of aeration is variable causing both increases and decreases with a general net effect of increasing bulk density but all the observed effects were small and sporadic compared to the regular fluctuations induced by changing water content throughout the year, for example the largest alteration in surface hardness from aeration was only 7% of the change induced by reduced moisture content.

Aeration treatments over the period measured and the application regimes used did not cause a compacted layer in the soil profile. The area of tine holes created by each aeration treatment is generally very small compared to the total area and estimates are that the tine holes created account for only 0.6-1.8% of the total volume. Given the minimal impact it is therefore not surprising that over only three years a compaction layer was not created. Repeated within-year treatments over a longer period of time may yet cause a compacted layer if set to the same working depth each time.

Air injection was shown to remove a compacted layer of soil in the profile but only in Soil K and was the only aeration treatment to do this. The pore size distribution of Soil K relative to Soil O was thought to be the cause of this allowing the force of the air to spread a greater distance through the soil than in Soil O. The difference between soils in containing the force of compressed air is thought to relate to the difference between the immediate effects of the treatment in Soil O and Soil K seen in Section 7.2.

Water content in Soil O was reduced by all aeration treatments due to increased surface area of the soil. Soil K, which has a greater natural evapotranspiration rate than Soil O (Shipton, 2008), was unaffected. The reduction in water content could increase the diffusion rate of gases in the soil facilitating the movement of oxygen into the soil and waste gases out of the soil increasing microbial activity and root depth. This was not reflected in the microbial biomass and organic matter content which showed no effect from aeration treatments, so either the microbial population was unaffected by increased oxygen availability or there was no increase.

The strongest influence on soil organic matter and microbial biomass populations was the general maintenance regime on the pitches which appeared to reduce organic matter and increase microbial biomass across all areas of the pitch.

7.4 Field Trials: End point trial excavation

Measurements of root density and infiltration rate were made for each aeration treatment. The infiltration data was too variable to show any clear effects. The root density data revealed generally no aeration effect except for the Deep Drill and Water Injection which increased root density by 13% and 28% respectively relative to the control. Across the entire test area there were no significant barriers to root growth which extended to at least 200 mm regardless of treatment. Visual assessment from inspection trenches revealed that tine holes can act as conduits for root growth and are often only sealed at the surface, persisting at depth. Biopores from the activity of earthworms were found to be widespread and extensive.

7.4.1 Experimental Approach

After the aeration trials were completed the pitches were further examined in April 2011 for:

- Dry root mass
- Qualitative visual assessment of aeration treatment effects
- Infiltration rate

Root mass was determined by taking cylindrical cores using 42 mm split corer (BMS Products Ltd, Luton, UK) from the surface to the top of the sharp sand layer (approximately 200 mm deep). The cores were wrapped in plastic film and sealed in individual bags before being placed in a cool environment (< 5 °C). Each core was carefully subdivided into four sections as per Section 7.3. Each core section was placed overnight on an end-to-end shaker with 150 ml of water and 50 ml buffered sodium hexametaphosphate dispersing solution. The resulting slurry was then washed over a 0.5 mm mesh sieve. The contents of the sieve were transferred to a bucket and the roots floated off onto a 0.1 mm mesh sieve. The contents of this sieve were then visually assessed and any non-root material removed. The remaining contents were transferred to a preweighed dish, dried at 105 °C for 24 h and the dry weight of roots recorded.

Infiltration rate was determined using a double-ring infiltrometer. Concentric rings were forced into the soil to a depth of 30-50 mm and water added to give a head of 50-75 mm. The water in the outside ring acts to minimise any lateral movement from the inner ring so that all water in the central ring is assumed to move vertically through the profile. The rate of inflow through the central ring is measured and the infiltration rate is recorded as the water intake rate once it becomes constant.

The visual assessment of aeration effects was determined from six 0.5 m wide trenches dug perpendicular to the long axis of the trial plots so that each trench crossed all seven plots (Figure 7.39). Three trenches were dug for each soil. The soils was visually assessed and further broken up by hand to look for evidence of the aeration treatments, such as tine holes, compaction layers and earthworm activity.

Figure 7.39 Photograph of experimental area in April 2011 showing a number of observation trenches spanning the width.

7.4.2 Results & Discussion

Infiltration rate data was so variable that no meaningful trends could be discerned. The soil was very dry which presented difficulties in embedding the rings in the soil. Potentially such damage was done to the soil structure in forcing the rings into the ground that when coupled with the natural variation of the soil, particularly in terms of shrink-swell behaviour and the formation of fissures spanning the soil profile, that no interpretable data was gained. Infiltration data was collected over a 14 day time period due to limited equipment and extremely long time taken for samples to reach terminal infiltration rate. Potentially this extended sampling period may also have contributed to the variability of the measurements. Finally, due to the slow nature of the work and limited equipment different sized concentric rings had to be used the results of which could not be reconciled with each other despite theoretically taking the cross sectional area into account during the calculations (Appendix C).

The root density data was analysed using Statistica 10 (Statsoft, Tulsa, USA). ANOVA revealed aeration, soil type, depth and soil type*depth as significant effects at $p<0.05$. Shipton (2008) found when examining the same soils for root density in a pot experiment that Soil K had a greater root density than Soil O which was attributed to the greater volume of large pores in Soil K relative to Soil O allowing easier penetration of the roots through the soil matrix. The same effect is seen here (Table 7.13).

Table 7.13 Mean root density over all treatments and depths in Soil O and Soil K.

Soil	Root Density (kg m^{-3})	
	Mean	St. Error
O	4.1	0.7
K	6.7	0.9

As was observed in Section 6 the root density declines with depth. At each depth Soil K consistently shows a greater root density than Soil O (Figure 7.40).

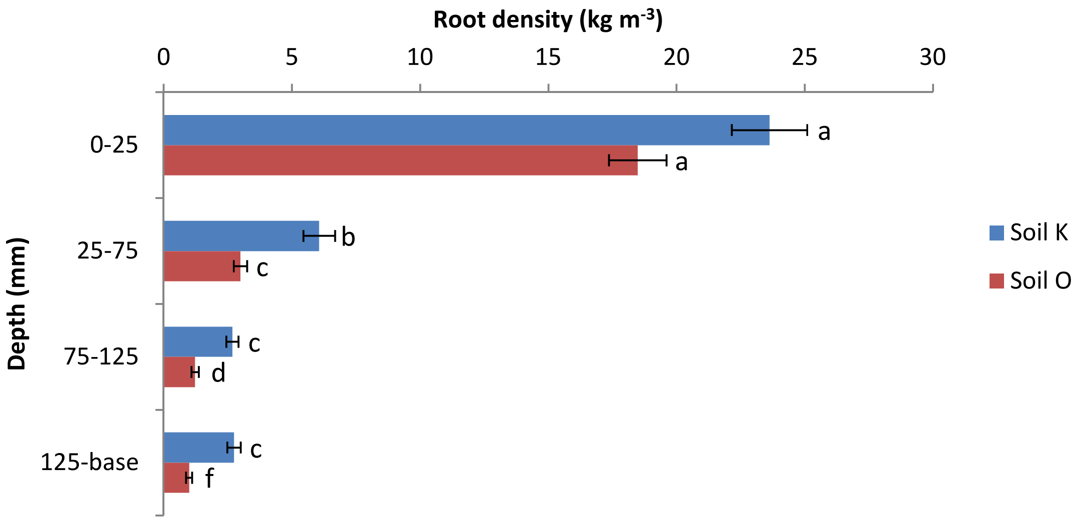


Figure 7.40 Mean root density over all treatments at each depth for Soil O and Soil K. Horizontal bars denote standard error. Letter indicate homogenous groups at p<0.05.

The behaviour of the root density in the profile with increasing depth and the magnitudes are similar to those found for the 1.20 g cm^{-3} and 1.55 g cm^{-3} units in Section 6. The mechanism behind this pattern is explained in Section 6 and will not be further discussed here.

Only the Deep Drill and Water Injection treatments were significantly different from the control, increasing root density in both soils (Figure 7.41).

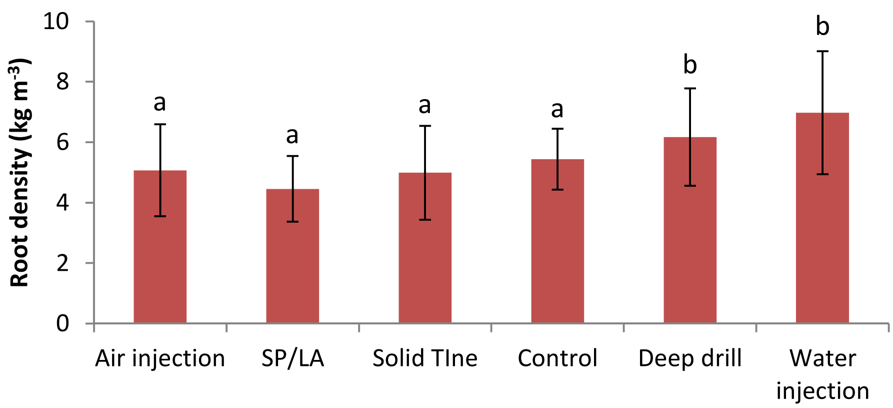


Figure 7.41 Mean root density over all depths for each aeration treatment. Treatments are arranged in same order as on the trial site. Vertical bars denote standard error. Letters indicate homogenous groups at p<0.05.

The increase in root density in the Deep Drill could be due to the growth of roots down the tine hole which were often filled with lengths of root (Figure 7.42). No such obvious features were present when examining the Water Injection soil profile which visually appeared no different from the control.

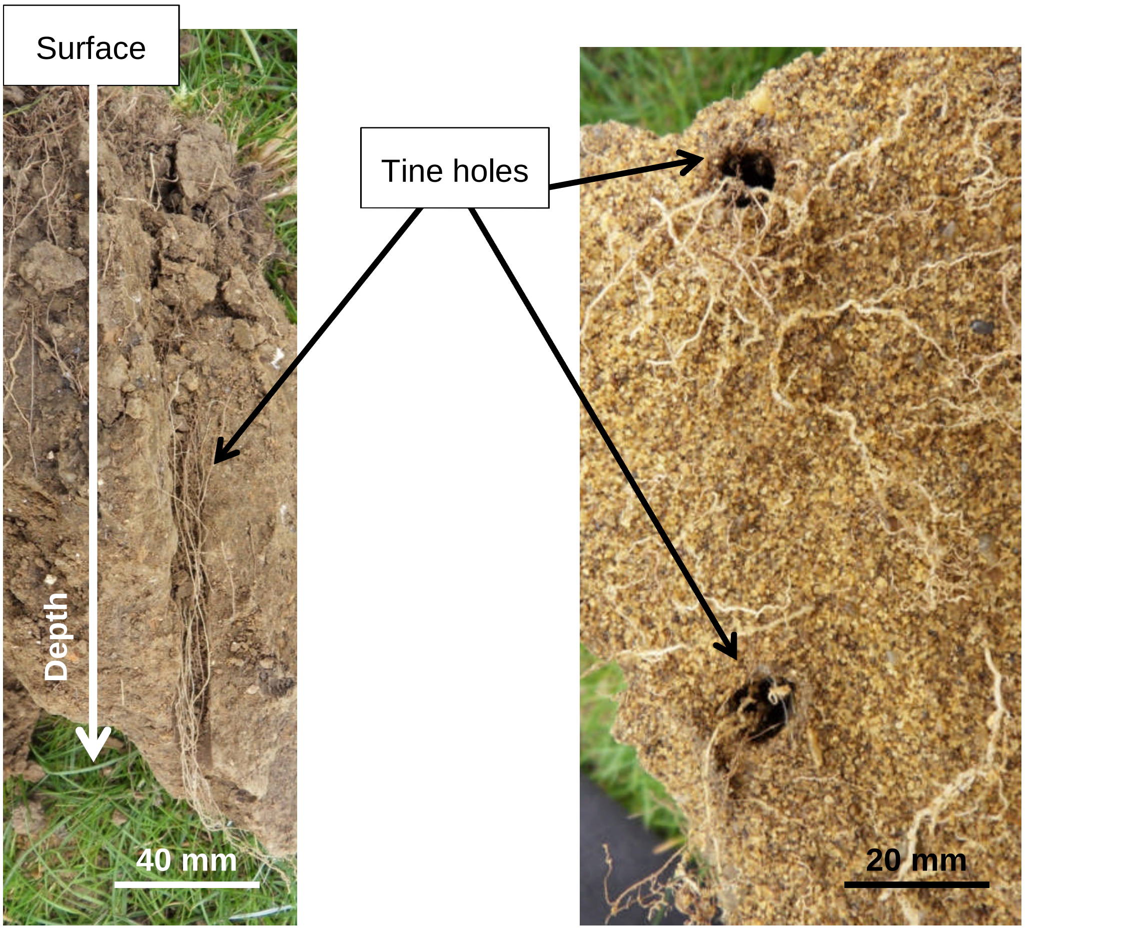


Figure 7.42 Section view through the profile (left) and view of the base of the profile (right) showing examples of growth of roots within Deep Drill tine holes

The presence of roots in tine holes was not limited to the Deep Drill and was observed for both Air Injection and Solid Tine treatments (Figure 7.43). There were no visible differences between the Linear Aeration treatment and the control. Given the presence of roots within the tine holes of other treatments, yet no significant increase in root density between those treatments and the control, an alternative theory on root density for the Water Injection and Deep Drill could stem from their location on the trial area. The trial site was constructed at a slight slope to prevent ponding on the surface. Both the Deep Drill and Water injection treatments are at the bottom end of the slope and so during a rainfall event may experience a greater input of water due to surface run-off from further up the slope. This was not reflected in the moisture content data (Section 7.3) but the root density data does appear to show an upward trend across the treatment area culminating in the significantly different Deep Drill and Water Injection values. The counter argument to this would be that the plants higher up the slope would have reduced access to water and as such would develop deeper root systems to extract more water from further down the profile to compensate and so would be expected to show greater root density at depth which was not observed.

If the increased root density is a consequence of aeration this could point to much longer lasting effects than have previously been realised given that there was no Water Injection treatment in 2010 leaving 17 months since the area was last treated.

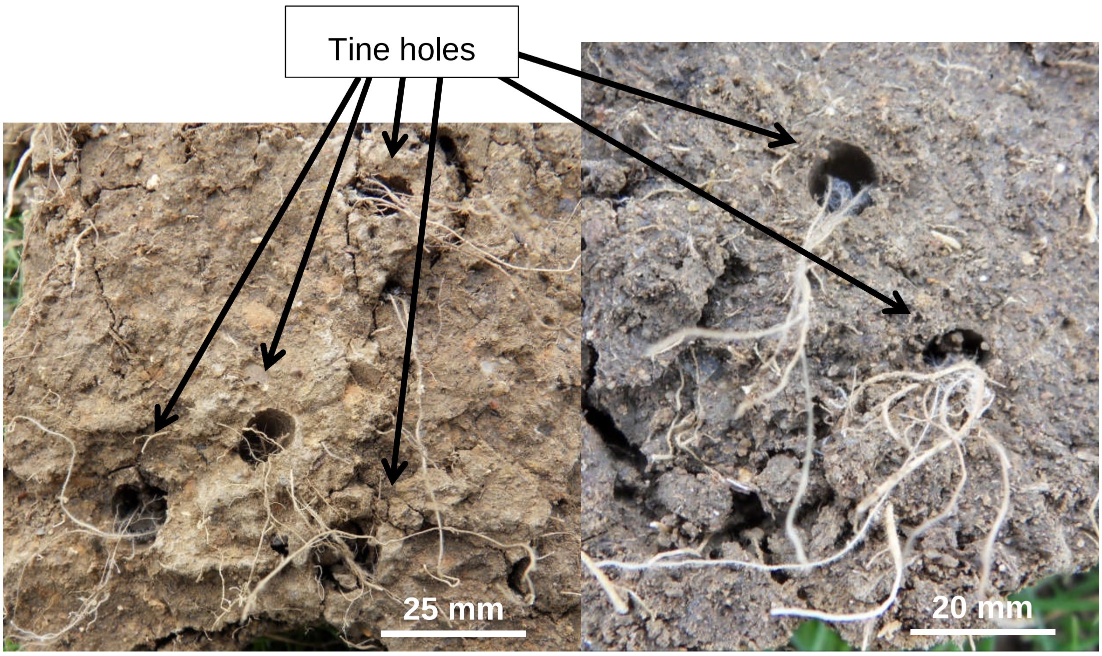


Figure 7.43 View through a cross section of soil (50 mm depth) looking up towards the surface showing root growth down the tine holes created by Air Injection (left) and Solid Tine (right) treatments.

The Deep Drill has the greatest working depth of all the aeration treatments. Gibbs *et al.* (2001) found the Water Injection had a working depth of 100-200 mm in a sandy soil – the working depth in this soil could not be established as there were no visible holes. Examining just the Deep Drill would lead to the conclusion that aeration needs to be greater than 75 mm depth to achieve an effect on root density, however more work will need to be done to confirm this.

In Solid Tine, Deep Drill and Air Injection treatments it was noted that the walls of the tine hole often remained smooth, visible evidence of smearing of the soil from these aeration treatments (Figure 7.44). The prevalence of tine holes remaining, which retain the shape and dimensions of the causal tine would indicate that the holes are not removed by shrink-swell as rapidly as was believed by examination of the surface only. The top of the tine holes tend to become sealed but the remainder persists in the profile adding further doubt to the hypothesis that aeration leads to increased shrink-swell beyond that seen in the bulk density data in Section 7.3.

Figure 7.44 Sectioned view of a tine hole left by the Deep Drill with the grooves of the drill still visible six months after treatment (left) and a sectioned view of three tine holes from Air Injection treatment showing distinctive smooth walls and tine shape (right).

There were no visible differences between soil types in terms of the aeration features seen or the root growth within them. Over all parts of the pitch, root growth was visible throughout the entire profile and particularly noticeable on the base of each sample were roots produced by the plant for exploration of the sand layer (Figure 7.45).

Figure 7.45 View of the bottom of the clay layer showing the thick mass of roots penetrating through to the sharp sand layer.

The prevalence of rooting spanning the clay loam layer to depths greater than 200 mm across all treatments would indicate that in this case restricted root depth is not a problem and aeration in the cause of increasing root depth here is unnecessary. It was noted in Section 7.3 that potentially the test area was too new and well maintained suffering none of the common problems associated with many cricket pitches such as layering and root breaks. Perhaps in a more damaged soil profile, rooting would have been more affected and aeration more effective. An alternative explanation for the effective rooting in the pitches could be due to the activity of worms. Dexter (1991) noted worms as a major source for the amelioration of soil compaction through the creation of biopores. Worm activity has always been noted in the pitches by the prevalence of casts on the surface. Examining the profile it was found that worm burrows could be large with extensive branching through the soil profile providing a natural means of aeration (Figure 7.46).

Figure 7.46 Photographed examples of extensive worm burrows through the soil profile (worm burrows are highlighted in white to aid identification).

7.4.2.1 Method limitations & suggestions for future work

The root density data presents a view at only one point in time. Grass growth over winter is severely limited and the sampling date was chosen to coincide with the peak spring grass growth rates as this represents the first opportunity the grass plant has to take advantage of the aeration treatment effects on the soil, thus theoretically providing the greatest scope for differentiation between treatments. Ideally a measure of root density would have been made over time similar to the repeated-measures sampling in Section 7.3 for density and moisture content. The effect of aeration on root growth may be more prevalent at other times or have effects over time that are not visible here. Reasons for this would include prevailing weather conditions, for example the winters of 2010 and 2011 were much drier than average (total precipitation was only 77% in 2010 and 80% in 2011 of the 1971-2000 average (Met Office, 2012)) and as such soil gas exchange may have been less restricted on average than during wetter winters where the effects of aeration could have made a larger difference (Section 8).

Like root density, the infiltration measurements would benefit from a repeated measure over time as a single reading may not capture the full effect. The very slow nature of taking the readings necessitates the work be done in parallel which will have implications on personnel and physical resources if the readings are to be taken within a time period where they can still be justifiably compared.

The visual assessment is limited to qualitative statements from which only tentative conclusions can be reached. However, the observations highlight the activity of worms in creating macropore systems within the soil profile that would be worth comparing to the artificial macropores created from aeration to see if worms present a natural, sustainable, effective and above all, cheap alternative to mechanical aeration. It is recommended that the laboratory and pot experiments examining gas diffusion and root density would benefit from the addition of an earthworm treatment. Further consideration would have to made of the negative effects associated with worm activity before making any official recommendations. While they may provide improved aeration the casts blunt lawnmowers blades and can smother the grass plant if they are not removed prior to any surface traffic. Worm casts have also been accused of adversely affecting ball bounce however this has never been properly investigated. Most of the negative effects of earthworms are associated with the cast they leave on the surface. Investigations into the performance of non-surface casting worm species in pitch improvement and how to encourage populations in cricket pitches to out-compete surface casting earthworms is a potential avenue of research to address this.

7.4.3 Summary and key points

The data presented here present limited scope for definitive conclusions due to the restrictions of the data in time and the qualitative nature of the visual assessment.

The presence of widespread rooting across the entire pitch reaching through the layers of clay loam and into the sand show little restriction on rooting in the test pitches regardless of any aeration treatments. Given that most of the aeration treatments had no significant effect on root density then aeration as a routine treatment would seem unnecessary if there are no problems with the pitch. If the pitch is suffering from root breaks and layering then aeration may be beneficial in providing channels for root growth that allow them to traverse these barriers as evidenced by the root growth within the tine holes in the Deep Drill, Air Injection and Solid Tine treatments. Using the Deep Drill or Water Injection treatments as routine maintenance increased root density through the profile by 13% and 28% respectively but given the extent of rooting present in the control this may have little added benefit. Extensive rooting has been cited as necessary for moisture removal but no link between the rate of removal and root density was found in pot experiments (Shipton, 2008). The danger of encouraging extra root growth is a build-up of organic matter within the soil, however, the organic matter measurements taken in Section 7.3 did not reflect this but for long term usage beyond three years this possibility cannot be ruled out.

The two aeration treatments that were effective in increasing root density have greater working depths than the other treatments, leading to a conclusion that, in terms of increasing root density, deeper is better when choosing an aeration treatment. However, generally the deeper the penetration of the machine the greater the required input of energy and also wear and tear. Deeper may not necessarily be better for vertically operated tine treatments such as the Solid Tine and Air Injection as a greater depth of penetration will increase compaction around the tine hole. Further research is needed to examine this.

The effect of the water injection could indicate much longer lasting effects from aeration potentially leading to a conclusion that annual aeration is unnecessary if the effects stretch for 17 months or longer. Unfortunately given that all the other treatments either had no effect or were applied annually this hypothesis cannot be further examined.

The activity of earthworms may present a natural means of soil aeration and amelioration of soil compaction. Extensive interconnected networks of pores created by earthworms were noted throughout the profile. In the past groundsmen applied pesticides to deter or kill earthworms for a number of reasons. Earthworms are considered a pest because of casts on the surface which can kill the grass by smothering the plant if they are not removed by brushing prior to working on the pitch, as well as blunting the lawn mower. In addition earthworms are believed to encourage weeds and potentially adversely affect ball bounce. Purging the pitches of worms will have prevented the negative effects listed above but has also removed a potential free and effective source of aeration. The effectiveness of earthworms cannot be quantified here but in lieu of further research a "live and let live" policy regarding earthworms from a soil aeration standpoint may reap considerable rewards. The negative effects of earthworms can mainly be negated by regular brushing of the pitch and chemical control of the weeds. For a well-resourced club this is less of a problem, however, for the voluntary groundsman working for a poorly resourced club this represents a considerable increase in the time, effort and expense required to maintain a pitch.

7.5 Field Trials: Conclusions and relevance to cricket

Upon examination of the immediate and long term effects of aeration the changes induced from seasonal weather patterns and the general maintenance of the pitches dominate the majority of measurements.

If the aim of aeration is to reduce soil compaction then the measurements of bulk density reveal that this is not the case. Any aeration effects on bulk density were small and changeable with no clear discernible pattern akin to the soil strength measurements in Section 7.2. No apparent correlation could be found between the changes in surface hardness and penetration resistance observed from the immediate effects of aeration with the long term trends observed in bulk density or water content beyond those caused by shrink-swell, freeze-thaw, water content variations and general maintenance regimes. Groundsmen, when asked, considered aeration to be important in decompaction from summer rolling (Section 3) the evidence here would suggest that the routine use of aeration equipment over three years for this purpose provided no observable benefit compared to natural processes.

Of the myriad observed effects from the immediate effects of aeration on penetration resistance and SH, only one was observed as significant in the long term measurements. The lack of treatment effects present in the surface hardness and penetrometer data in the long term measurements corroborates previous research in sandy soils that most aeration effects are short lived. Only Air Injection caused an effect noticeable in both the immediate effects and the long term effects, where the DMR was moved to a greater depth in Soil K. The demonstrated effect of removing a compacted layer in the soil from Air Injection could indicate potential for this technique in relieving compaction in the soil profile more efficiently than no treatment or solid tining alone yet it is limited in effectiveness by the pore size distribution of the soil so careful examination of the pitch is required to determine if the technique will deliver any benefit over solid tining alone (or no treatment).

The total surface area can be vastly increased from aeration treatments. The increased surface area caused a net decrease in water content in Soil O relative to the control but not in Soil K. Section 5 showed even small changes in water content can profoundly affect the diffusion rate of gas in the soil and consequently the oxygenation status. By reducing water content of the soil, the connectivity of the pore network is increased and the tortuosity decreased as more pores remain empty. This allows less restricted diffusion of gases through the soil, supplying oxygen for microbial and root activity, potentially allowing for the formation of deeper root systems and greater microbial activity although this was not reflected in the microbial biomass or organic matter data. The root density data only showed increases from the Deep Drill and Water Injection treatments so seem unaffected by the water content reduction (otherwise increased root density would be expected across all aeration treatments). The lack of perceived benefit from the lower water content could be due to the reduction not being sufficient to cause any secondary effects or that the lack of layering or other problems in the pitch, coupled with the activity of earthworms, ensured the pore network was more than capable of supplying the oxygenation demands of both the roots and microbes. For pitches that suffer from anoxic conditions from high water contents or soils that have a high bulk density and therefore a more reduced pore network, routine maintenance with aeration would confer considerable benefit by reducing water content. If the soil is well structured or the soil is sufficiently good at removing water either via drainage or evaporation on its own (like Soil K) then aeration will provide little additional benefit from reduced water content as is observed here.

A second benefit from decreased water content is the potential for the soil to warm more quickly in spring allowing for a longer growing season, though the very small difference in water content would probably not lead to a noticeable change.

Over the autumn-winter period water supply far outweighs the demands from the plant as evidenced by the recovery of PSWD to zero by December each year. However if the tine holes do not disappear over the period due to shrink-swell as was evident in Section 7.4 the increased surface area and evapotranspiration could potentially lead to the pitches drying out more quickly and hence to increased and uncontrolled cracking. Though there was no evidence in these trials to support this.

Aeration was highlighted as a cause of compacted layers within the soil, particularly when using solid tines (Rieke and Murphy, 1989) however no evidence was found over three years of repeated treatments of the formation of a hard pan from aeration. In Section 3 some groundsmen reported using the same equipment repeatedly for ten years or more, possibly over such an extended period of time a compacted layer could build up. The possible reason for a lack of compaction over just three years is due to the small area that is affected by each aeration treatment. For each treatment, the tine holes created represent less than 2% of total volume. Over the time period of three years such a small additive effect may not amount to much, but over ten years or more particularly if there are repeated aeration applications each year a significant area may be affected, causing a compacted layer to build. The low impact on the total volume of soil by most aeration treatments could account for the small amount of observed effect. In golf courses where hollow core tining is used to control water content, the efficacy of treatment is only attained by repeated treatment and is measured by the volume of soil removed and consequently replaced so that potentially aeration treatments in cricket are not being applied enough to have any effect. Further research is needed as to the possible balance that must be made between increased compaction from a high level of repetitive solid tining relative to any possible benefits.

The Deep Drill and Water Injection treatments showed increased root density relative to the control, though this increase appears to be related more to location on the trial site than due to aeration treatments. It was noted that often there was considerable root growth down the tine holes where tine holes were observed (Air Injection, Solid Tine and Deep Drill) but the presence of tine holes alone did not sufficiently explain the observed trend in root density compared to location. Therefore no definitive increase in root density can be conferred to any aeration treatment.

It is recommended then that groundsmen have a firm understanding of the nature of the soils making up their pitches, understanding that the effectiveness of aeration is determined by pore size which is in turn related to density and the particle size distribution of the soil. Soils with a greater average pore size may benefit more from Air Injection than soils with a smaller average pore size. Conversely soils with a small average pore size may benefit from all tested aeration treatments (except Spiked Roller) due to reduced water content. Generally pitches that demonstrate no inherent problems (i.e. are not layered, do not have shallow rooting) would be unlikely to benefit from aeration. The phrase “if it is not broken, do not fix it” appears to apply aptly to this situation. If the pitch does suffer from anoxic conditions (sitting wet, layering or extremely high bulk densities) then aeration may deliver some benefits from increased surface area and reduced water content that were not seen here. Potentially the greater drying potential of aerated soils could lead to a greater level of shrink and swell as the soil is able to shrink more between rainfall events due to the greater ability to remove water but the bulk density measurements do not support this hence aeration as a matter of routine seems to confer no additional benefit over natural processes.

Aeration in layered pitches may be beneficial in providing channels for root growth as observed in Section 7.4, particularly if the tine holes are deep. Common practice currently is to use either the Deep Drill or Solid Tine to a working depth that exceeds the depth of layering to provide channels for root growth that will hold the pitch together as the roots grow through the underlying soil. The mechanical properties of a layered pitch bound with roots have not been tested so the effectiveness of the technique cannot be evaluated beyond the anecdotal but the observed root growth would support the theory that tine holes provide channels for root growth. Layered pitches with the right pore size distribution (similar to Soil K) may benefit from Air Injection treatment particularly if the problem relates to a layer of densely compacted soil, however, the effectiveness of the technique in the context of a pitch suffering a horizontal break may do more harm than good as the break will most likely represent the path of least resistance for air flow.

The effects observed in these experiments indicate that good rolling and general maintenance is more important than aeration in maintaining a healthy, performing pitch. The observed effects are limited to those in a pitch that does not have root breaks or layering so aeration may be more effective in these situations. With this in mind it may be more likely that aeration should be used as a tool to solve specific problems rather than as routine maintenance as the benefits inferred are limited in the context of a healthy profile given that natural processes of soil amelioration from shrink-swell and frost heave dominate over any observed effects of aeration shown here.

8 Effect of aeration on the soil atmosphere in the field

Two cricket pitches were constructed with in-situ gas sampling equipment. One pitch was retained as a control and was not aerated; the remaining pitch was aerated using vertically operated solid tines (VOST). The aeration treatment was shown to be effective at increasing oxygen concentrations following rainfall events but at other times was not significantly different from the control.

8.1 Introduction

Laboratory studies have shown that VOST aeration does increase the rate of oxygen diffusion into the soil (Section 5). The laboratory experiment was conducted on repackaged soil without grass plants. Attempts to replicate the experiment with grass were not successful. This field study aims to determine if gas exchange between the soil air and free atmosphere is restricted. Oxygen concentrations will be monitored to assess whether they are a limiting factor on root growth and whether aeration significantly increases the oxygen concentration. At the same time carbon dioxide and other waste gas, notably, nitrous oxide (N_2O) and methane (CH_4), concentrations will be measured to assess for anaerobic conditions and whether potential build-ups of waste gases could damage plant growth.

8.2 Monitoring of soil atmospheres

Soil air composition is a direct measure of the lack of equilibrium between the free atmosphere and respired soil gases due to impeded gas transport (Stępniewski *et al.*, 1994). There are a number of problems associated with the monitoring of gas concentrations in soils, especially with regards to validating the accuracy of samples against the actual soil atmosphere. A number of systems have been proposed to overcome the logistical and technical problems of measurement. Laboratory experiments conducted in controlled conditions present greater problems than other *in vitro* assessments of soil parameters. Moldrup *et al.* (2000) showed that there was a considerable difference in the gas diffusivity of soils that had been repacked in the laboratory and undisturbed soils. The undisturbed soil samples showed a much greater dependency on soil type. Therefore in a sports surface system field sampling represents the most appropriate mode of assessment. The main methods of soil atmosphere monitoring are examined below.

8.2.1 Point sample extractions

Point sample extractions are described as a “snatch and grab” technique and usually consist of a tube with an opening at the top and bottom, the tube is driven into the ground to the desired depth and a sample extracted from the upper opening. This technique presents the problem of ensuring a tight fit of the tube walls to the surrounding soil. If the seal fails then there is likely to be flow vertically between the soil and the outside of the tube, making it impossible to determine the depth at which the sample has been taken. Error of this type is further amplified by the method relying purely on mass flow of the gas in the extraction technique. Preferential flow from larger pores relative to smaller pores may mean that the sample is not representative of the soil atmosphere in all pores and the sample may also not be from the immediate surroundings. Results from the use of this technique vary widely (Stępniewski and Gliński, 1985; Smith and Conen, 2003) and in the shrink-swell soils of a cricket pitch maintaining the seal between the tube walls and the soil will be extremely difficult. Also, in the summer time when the pitches are particularly hard the sampling equipment would have to be particularly robust to withstand being driven into the ground.

8.2.2 Buried sensors

Buried soil gas sensors adopt a passive technology approach to assessment. Once the sensor array is installed in the soil it consumes a minute volume of the sample gas (Liang *et al.*, 2004; Tang *et al.*, 2003). The soil atmosphere is monitored continuously without significantly affecting the concentration gradients or inducing mass flow. Some studies using sensors have taken the approach of building subsurface diffusion chambers to house the sensor (Liang *et al.*, 2004). Chambers have typically been made from microporous materials that are impermeable to liquid water so as to protect the sensor but allow gases to diffuse into the space for monitoring. The buried sensor approach to soil atmosphere sampling can be prohibitively expensive especially if several depths are to be monitored in parallel.

8.2.3 Buried gas wells

In studies where long term monitoring or repeated sampling of a single area is required then the installation of permanent gas wells or diffusion chambers may be appropriate. Such systems usually consist of a tube leading from the surface to a large, porous walled diffusion chamber. The soil atmosphere equilibrates with the void space of the chamber and a sample is extracted via the surface connection. This technique gives access to a wider cross section of the soil for greater spatial integration and the gradual equilibration with surrounding soil gives good temporal integration of the surrounding soil atmosphere (Stępniewski and Gliński, 1985; Smith and Conen, 2003). Mass flow is unavoidably induced during sample extraction. The system can be designed to reduce the mass flow by using relatively small sample volumes and large void spaces in the gas well. Repeated extractions are limited by the time taken for the atmosphere in the chamber to return to equilibrium with the soil atmosphere. The connectivity of the sampling apparatus with the soil surface is also important to maintain accuracy in sample gas concentrations. This is particularly important when considering their use for the long term monitoring of a cricket pitch soil system. Soils with high clay content lead to shrinking and swelling in association with changes in soil water content. This continual shrinking and swelling is hypothesised to lead to gaps between the soil and surface connection creating essentially a large macropore connection to the surface.

8.2.4 Subsurface continuous pipe systems

Buried, closed-loop, pipe systems represent an alternative to the methods outlined above. Gut *et al.* (1988) and DeSutter *et al.* (2008a) proposed systems using buried porous tubing through which soil gas could diffuse but to which liquid water was blocked. The atmosphere inside the tube is subsequently analysed to determine the concentrations of the soil gases of interest and then returned back into the buried tubing. As this system does not remove any gas from the soil system the physical processes affecting the ingress of gas into the tubing remains dominated by diffusion. The tubing material plays a pivotal role in both system design and functionality and the properties of the most frequently used types of tubing were recently reviewed by DeSutter *et al.* (2006). They concluded that silicone tubing presented the greatest barrier to diffusion and showed that it took up to 10 hours for samples to reach equilibrium across the membrane. They also demonstrated that synthetic microporous tubing materials such as polyethylene attain 95% equilibrium within 8 minutes. Sampling from any closed loop experimental setup must therefore take account of this systematic lag time. The benefit of the closed loop system is that the closed loop means that the connections to the porous sections can be longer and so the sampling apparatus can remain off to the side of the pitch allowing the surface to be played upon without interference to the plays of sampling ports on the pitch itself. This also has the benefit of removing the surface connection to a greater distance from the sampling area with the connecting tubes running laterally through the soil thus reducing a source of potential error seen with buried-gas wells and point sampling.

8.3 Experimental method

Two adjacent cricket pitches were constructed at the Cranfield site from Boughton County™ clay loam (34% clay, 30% silt, 36% sand). The soil profile consists of 200 mm of clay loam over the natural soil, constructed in three equal layers. The area was seeded with a mixture of perennial ryegrass (*Lolium perenne*) varieties: 40% Sauvignon, 30% Evita and 30% Cassiopea. A sowing rate of 50 g m^{-2} was used with the addition of fertiliser (12:9:6 N:P:K) at 25 g m^{-2}. 36 lengths of porous tube (Porex GmbH, Germany) were buried at three depths (DeSutter *et al.*, 2008a; DeSutter *et al.*, 2006; DeSutter *et al.*, 2008b) within the profile (140 mm, 180 mm and 220 mm) (Figure 8.1). The 140 mm depth was chosen so that recommended aeration depths of 100 mm could be achieved without puncturing or damaging the tubing.

Figure 8.1 Photograph of the porous tube being laid during construction of the pitches (left) and picture of the completed and levelled pitches (right).

Each pipe section consisted of 914.4 mm length of porous tubing sealed at each end with a pre-drilled rubber bung sealed around a 7 mm PTFE pipe connector (Figure 8.2)

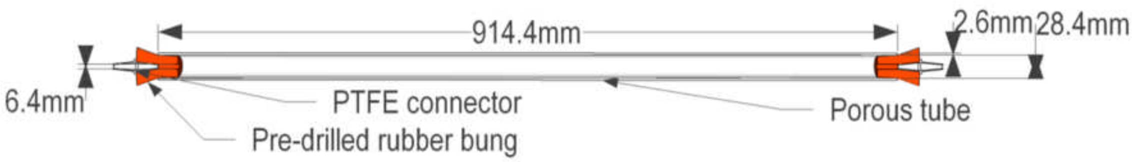


Figure 8.2 Cross section of a single buried porous pipe unit. Diagram is to scale.

The pipe units were laid in Z-like patterns across the width of each pitch at each depth, displaced so as not to overlap by 200 mm, to create a sampling array of nine units (Figure 8.3).

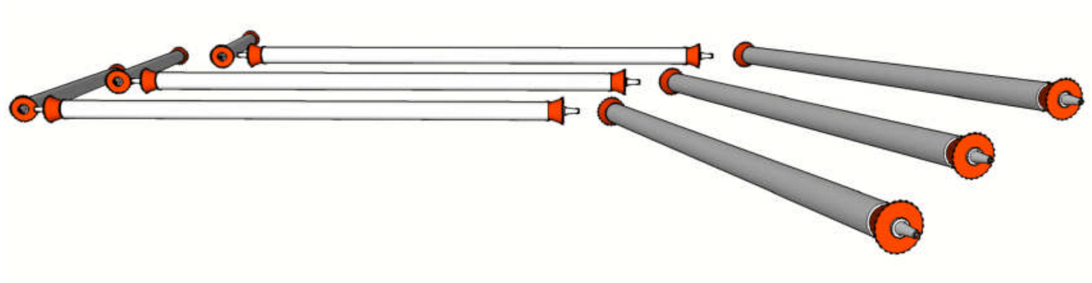


Figure 8.3 Nine porous tube units arranged in a non-overlapping Z-pattern array illustrating the positioning at each sampling location. Diagram is to scale.

Two arrays were built in each pitch; one was constructed 1.85 m from the end of the pitch and another 7.67 m from the same end of the pitch as measured to the centre of the middle tube at depth 180 mm for each array (these locations shall henceforth be known as the Wicket and Centre, respectively). The same dimensions and layout were used in the second pitch but from the opposite end to the first pitch (Figure 8.4).

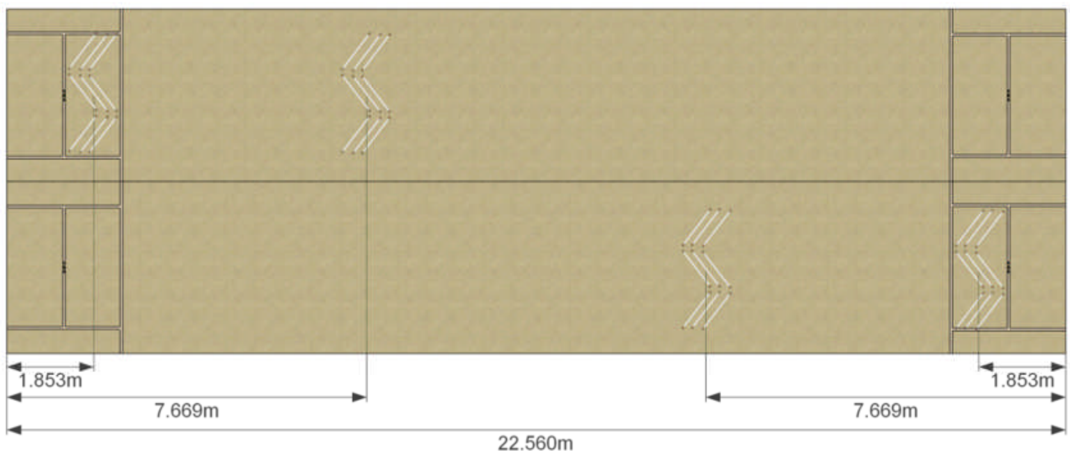


Figure 8.4 Plan view of the two pitches showing the sampling arrays in location. Wickets and creases are included to show the location of the tubing in relation to the game and expected level of wear.

The porous pipe was connected by lengths of reinforced PVC pipe (5 mm internal diameter) continuing at the buried depth and leading to an extraction chamber and valve system for connection to the pump for circulation of collected gas ready for sample extraction. The extraction chamber had a volume of 250 ml designed to smooth the cyclic pressure variations caused by the pump when circulating. The chamber was fitted with a butyl-rubber septum and samples collected in 10 ml evacuated Vacutainer® vials (BD, NJ, USA). The pump connections were fitted with a valve to seal the system when not in use. The extraction chamber and pump connections were contained within a buried manhole the top of which was flush with the surface of the soil and outside the area of the pitches allowing the pitches to be treated and played on normally without hazard (Figure 8.5).

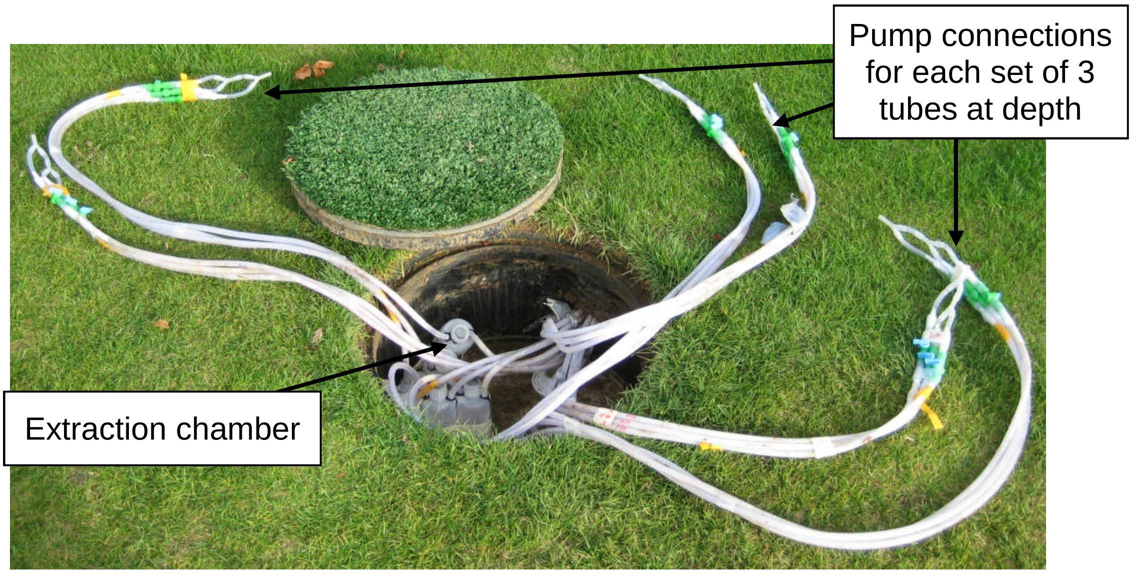


Figure 8.5 Buried manhole showing the connections for circulating the gas in the system and extraction chambers for collecting samples for a single sampling array.

The pitches were left to 'settle in' for one year as per recommended guidelines (ECB Staff, 2007). The two test pitches were incorporated into the standard maintenance regime of the remainder of the cricket square from October 2009 but were not aerated that year. The pitches were rolled along with the rest of the square but not prepared for matches that year. In late October 2010 one pitch was aerated using cam-action, vertically operated, solid tines (VOST) to 100 mm (with no heave), tine diameter was 7 mm, tine hole spacing was 50 mm in a square packing arrangement. There was no repeat treatment. The remaining pitch was not aerated. The pitches were prepared for matches in the Summer of 2011 and a number of games were played over them including some practice sessions. Players reported good even pace and bounce.

One sample was taken from each porous tube per day at the same time for three days. The pump was connected to each end system and the gases circulated for a period related to total system volume so that one half-cycle was achieved, i.e. the gas in the porous tube was exchanged for the gas within the sample chamber (Table 8.1).

Table 8.1 Timing for pumping of each porous tube system assuming flow rate of 400 ml min^{-1}. Tube numbers relate to each Z-arranged layer, Tube 1 corresponds to the unit closest to the covered manholes.

Aerated pitch		Control pitch	
Tube	Pumping time (s)	Tube	Pumping time (s)
1	49	1	57
2	54	2	62
3	59	3	68

Three days of samples were taken in August 2010 prior to any aeration treatments and then on a three month basis in November 2010, February 2011, May 2011, and August 2011. Soil volumetric water content was recorded using a Theta Probe (Delta-T Devices, Cambridge UK).

Samples were analysed using gas chromatography (GC 500 Series, Cambridge Scientific Instruments, UK) on a dual molecular sieve/porous packed CTR 1 column (Grace, IL, USA) with a thermal conductivity detector

Table 8.2 Settings used for sample analysis on GC 500 Series gas chromatograph.

GC Settings	
Injector	150 °C
Column	50 °C
Detector	100 °C
Filament	320 °C
Inlet pressure	0.34 Bar

The results in August 2011 were analysed to assess any inherent differences between the two pitches. Subsequent samples were analysed using repeated-measures ANOVA to assess any differences found between the two pitches over each three day period and over the entire sampling period. All statistical analysis was calculated using Statistica 10 (Statsoft, Tulsa, USA).

The weather data was recorded approximately 700 m from the test area.

8.4 Results

8.4.1 August 2010

The two pitches were not significantly different, nor were the locations (Wicket or Centre) or different depths when examined irrespective of days. The mean oxygen concentration was 19.0±0.1 %volume (%v). There was some daily variation due to a rainfall event (7 mm) that occurred post-sampling on the first day. This reduced oxygen concentrations on the second day in both pitches and raised carbon dioxide concentrations (Figure 8.6).

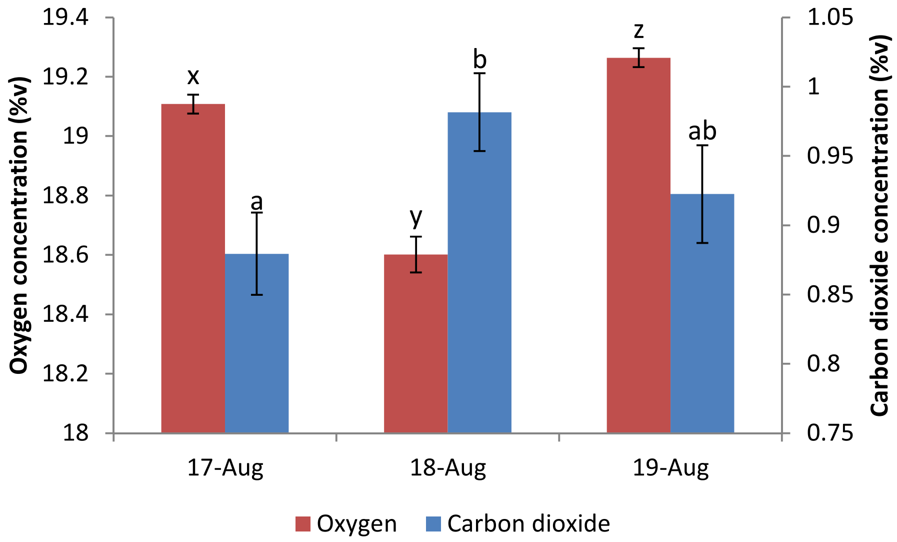


Figure 8.6 Mean oxygen and carbon dioxide concentrations over each pitch and location for each day in August 2010. Vertical bars denote standard error. Letters indicate homogenous groups at $p<0.05$.

There was some variation between the pitches and locations in the three day period but all showed the same general response of reduced oxygen concentration in response to the rain which had recovered by the third day (Figure 8.7). The total change in oxygen was small and nowhere did it drop below 18.5%v nor rise above 19.4%v.

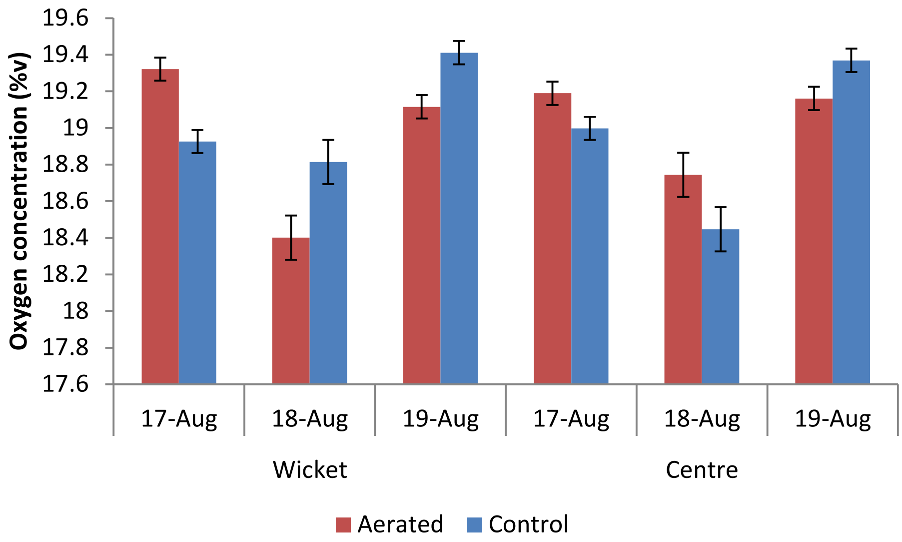


Figure 8.7 Oxygen concentration in each pitch at each location over the three day sampling period in August 2010. The labels 'aerated' and 'control' are to differentiate the two pitches, no actual treatments had been applied at this point. Vertical bars denotes standard error. Letters indicate homogenous groups within each day and pitch at p<0.05.

Only on Day 2 was there a difference in depth but not between pitches with the 140 mm depth showing a lower oxygen concentration in the Centre (18.4±0.2 %v) than at the wickets (18.7±0.3 %v). The remaining days showed no difference between depths, nor were there differences between Day 1 and Day 3 at each depth.

The reduced oxygen concentration is linked to 7 mm of rainfall that occurred over a single hour post sampling on Day 1. The response in each location to rainfall was the opposite in each pitch, both showed reduced oxygen concentrations in response to rainfall but in the aerated pitch (as yet untreated) the Wicket location showed the greatest reduction whereas in the control pitch the Centre showed the greatest reduction.

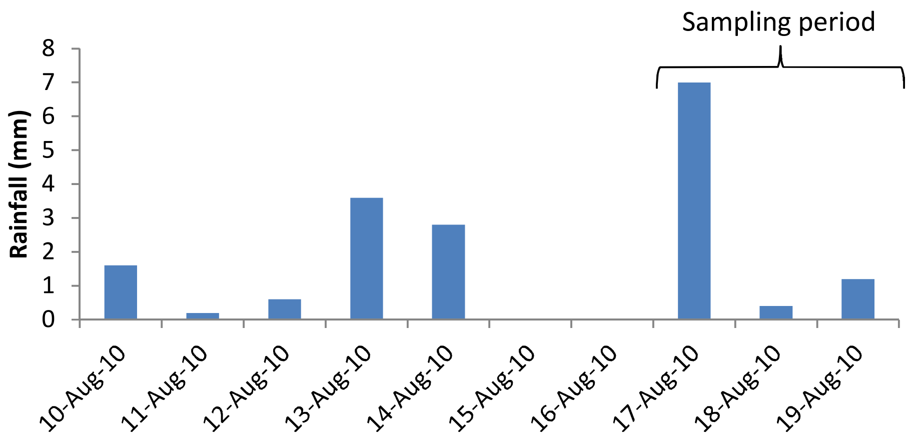


Figure 8.8 Rainfall recorded in the week preceding and during sampling in August 2010.

8.4.2 Aeration

The aerated pitch has a slightly greater oxygen concentration compared to the control pitch when averaged over both locations, all depths and all time points (Table 8.3).

Table 8.3 Mean oxygen concentration over all locations, sampling times (excl. Aug-10) and depths in the aerated and control pitch.

Pitch	Oxygen concentration (%v)	Standard Error
Aerated	18.73	0.06
Control	18.44	0.07

The difference is primarily due to the Wicket location as the Centre in both pitches were not significantly different (Table 8.4).

Table 8.4 Mean oxygen concentration over all sampling times (excl. Aug-10) and depths at each location in the aerated and control pitch.

Location	Aerated		Control	
	Mean	Standard Error	Mean	Standard Error
Wicket	18.98	0.09	18.45	0.11
Centre	18.49	0.08	18.43	0.09

Breaking it down by time points reveals a large dependency on recent weather as well as the water content of the soil at that time (Figure 8.9). Noticeably there are no significant differences at any time point between the aerated and control pitch in the centre location. In the wicket location only two time points show a significant difference between the aerated and control pitches, Feb-11 and Aug-11.

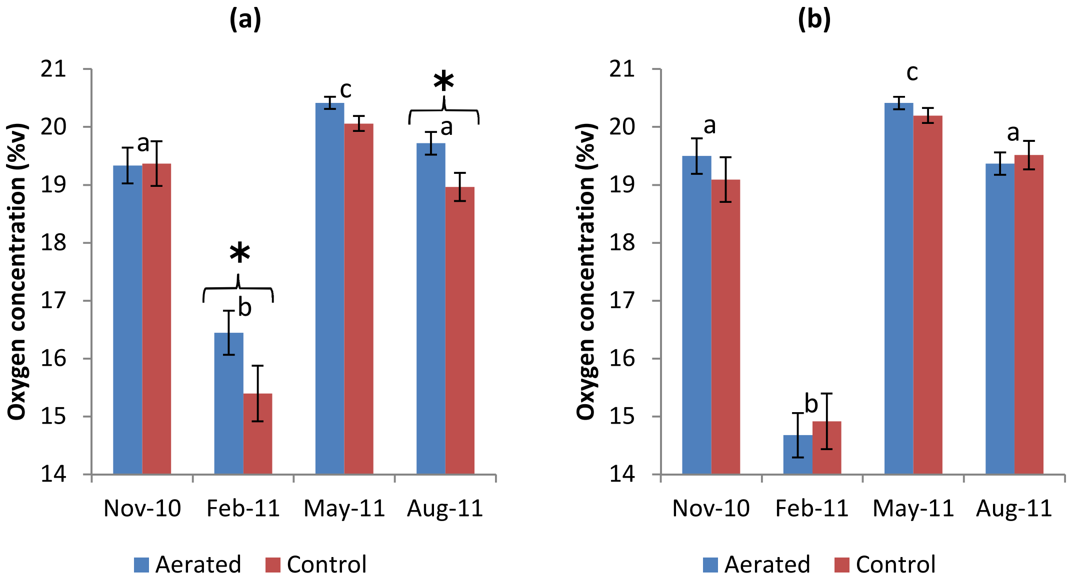


Figure 8.9 Oxygen concentration at each time point in each pitch at the wicket (a) and centre (b). Vertical bars denote standard error. Letters indicate homogeneous groups over time at p<0.05. ∗ indicates a between-treatment significant difference at p<0.05.

When separated out over the individual sampling days there is an aggregation of daily differences in oxygen concentration in February 2011 and August 2011 in the Wicket location between the aerated and control pitches, with only two points outside of these dates, only one of which is in the Centre (Figure 8.10). This leads to two key points, only the Wicket location appears to demonstrate an aeration effect and aeration effects are only observed at times after significant rainfall.

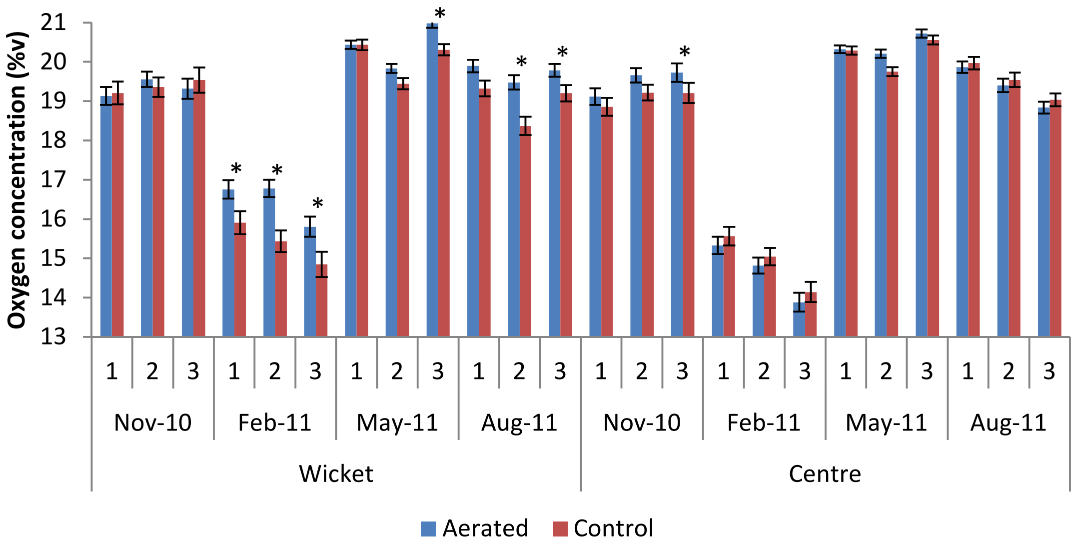


Figure 8.10 Mean oxygen concentration over all depths for each pitch, location, and sampling day for all time points. Vertical bars denote standard error. ∗ indicates a significant difference between aerated and control values at p<0.05.

8.4.3 Water content and rainfall

Table 8.5 details the recorded volumetric water content which shows a clear peak in water content in Feb-11 which corresponds to the low value of oxygen concentration recorded at that time.

Table 8.5 Mean volumetric water content over the sampling period at each time point.

Time	Water (cm^3 cm^{-3})
Nov-10	0.27
Feb-11	0.37
May-11	0.16
Aug-11	0.16

The oxygen concentrations in Nov-10 and Aug-11 are not significantly different yet show distinctly different water contents yet Aug-11 and May-11 show the same water content but different oxygen concentrations. The water content measurement was only in the top 100 mm which was above the shallowest buried tube so there may be wetting front effects that cannot be determined.

However, the top 100 mm could be argued as one of the most important regions as this is closest to the surface and determines access to the free atmosphere. Using the data available water content alone cannot explain the data.

It is a combination of total water and rainfall events that leads to the overall pattern. Total moisture in Aug-11 was significantly lower than in Nov-10 but the sampling in Aug-11 occurred a day after two days of heavy rainfall. Similarly sampling in Feb-11 occurred the day after a rainfall event which from the Aug-10 results were shown to cause oxygen concentrations to drop (Table 8.6). The small amount of rainfall in May appeared to have no effect either evaporating or absorbed into aggregates or surfaces with minimal impact on the pore network.

Table 8.6 Rainfall recorded at the Cranfield site over the sampling period and the week preceding sampling at each time point.

	Rainfall (mm)			
Days preceding sampling	Nov-10	Feb-11	May-11	Aug-11
7	0.2	1.4	0	0
6	0	0	0	1.4
5	0	0	0	0
4	0	0	0	2
3	0.2	10.8	0	30.8
2	0	0.2	0.4	5.2
1	0	8.4	0.2	0
Sampling days				
1	0.2	0	0	0
2	0	3.4	0	0
3	0	0	2.8	0

8.4.4 Temperature

Alternatively the difference between May and August 2011 could be due to temperature. The respiration rate of organisms within the soil has been shown to depend on temperature. Generally a higher temperature (up to a point depending on the organism) leads to an increased rate of respiration, assuming sufficient nutrient and water availability (Tang *et al.*, 2003). Examination of the temperature over each sampling time point shows a slight peak in the air temperature on Day 2 in May-11. This could have boosted the respiration rate slightly causing the slight decrease in observed oxygen concentration on that day (Figure 8.11).

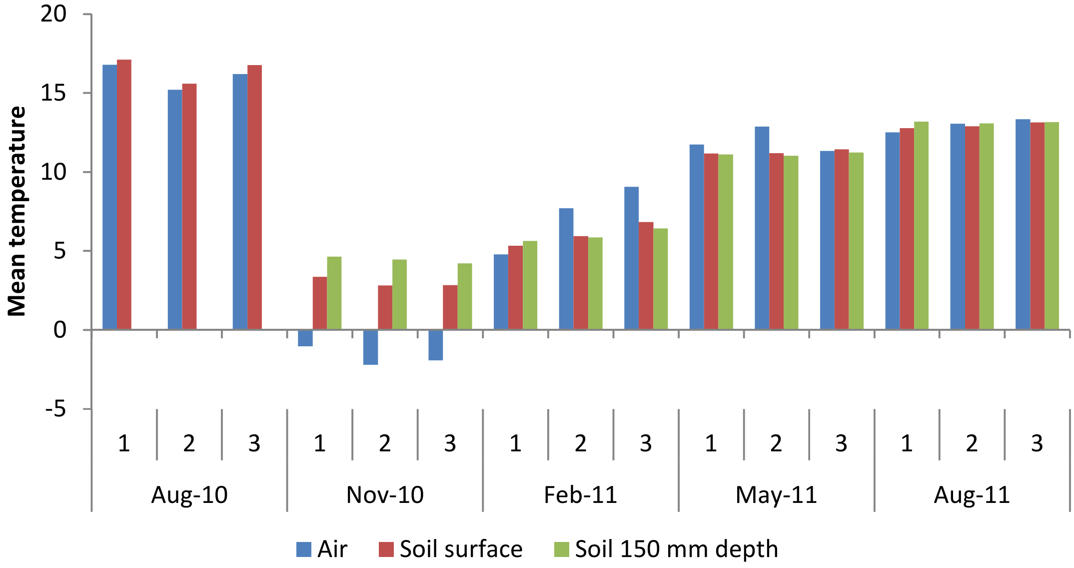


Figure 8.11 Mean daily temperature in the air, at the soil surface and 150 mm below the soil surface as measured at the weather station approximately 700 m from the test pitches. No soil temperature data was available for August 2010.

The temperature is clearly warmer in August 2011 than May 2011 so the respiration rate of the soil would be greater in August 2011 which could explain the decreased oxygen concentration. August 2010 was warmer than August 2011 and had a slightly lower oxygen concentration of 18.98±0.06 %v compared to 19.38±0.1 %v in August 2011. The concentration differences between time points due to temperature are very small in comparison to the effect of water content and rain in February 2011,

At all time points except Feb-11 the temperature remains consistent between days. The lack of observed temperature effects in February could be due to the lower overall temperature so that biological activity was reduced or that the effect of the high water content and rainfall over that period was dominant over the influence of temperature.

Due to the shrink-swell nature of the soil and rolling through the summer one final possibility presents for the difference between August 2011 and May 2011 due to changes in bulk density. Roots attempting to penetrate a compacted soil have been shown to have increased respiration rates (Stępniewski and Gliński, 1985), so the reduction in August 2011 relative to May 2011 could be due to increased mechanical impedance to root growth from increased density. There are complicating circumstances as high density soils are negatively correlated with root density and as such a drop in respiration rate could be expected but this is related to a consistent soil density rather than one which is fluctuating with water content. No research could be found on the relationship between shrink-swell cycles and root respiration response.

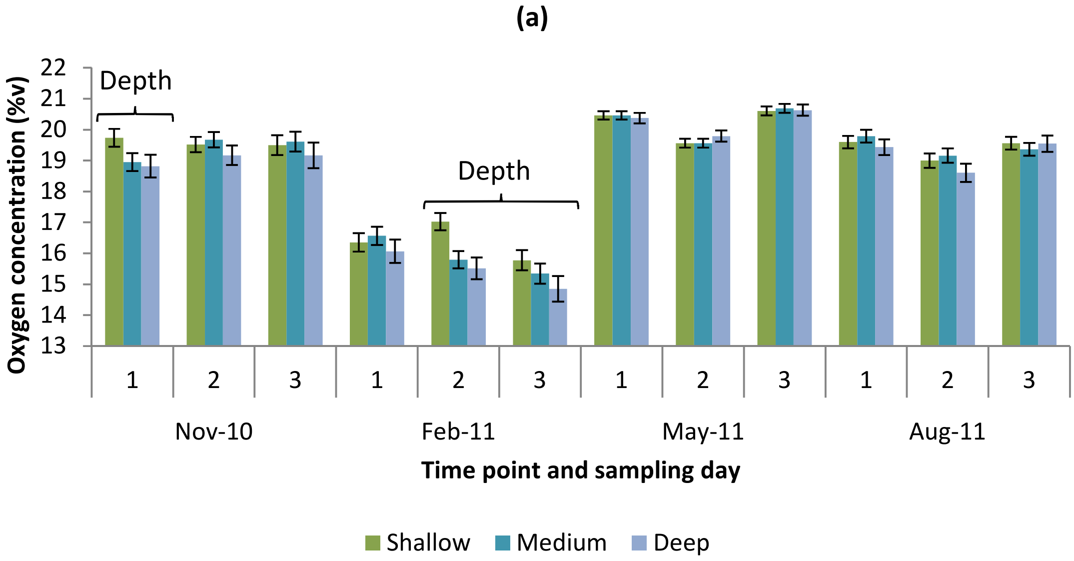
8.4.5 Depth

Differences between depths were only seen when examining individual days and corresponded with rainfall events. At each point the shallowest depth was always different from the two deeper levels, which were invariably not significantly different from each other (Table 8.7).

Table 8.7 Locations and times of significant differences in oxygen concentrations between depths. W refers to a difference in wicket location but not centre, C refers to a detected difference in centre only, W&C marks a difference in both locations.

Sampling days	Nov-10	Feb-11	May-11	Aug-11
1	W			
2		W&C		
3		W	C	

Generally the shallow depth exhibited a greater oxygen concentration than the deeper tubes (Figure 8.12). There was no difference between aerated and control pitches regarding changes with depth, nor with regard to differences between days at each time point, indicating that the short term responses of the pitches are the same regardless of treatment and that the effects of aeration emerge over a longer period.



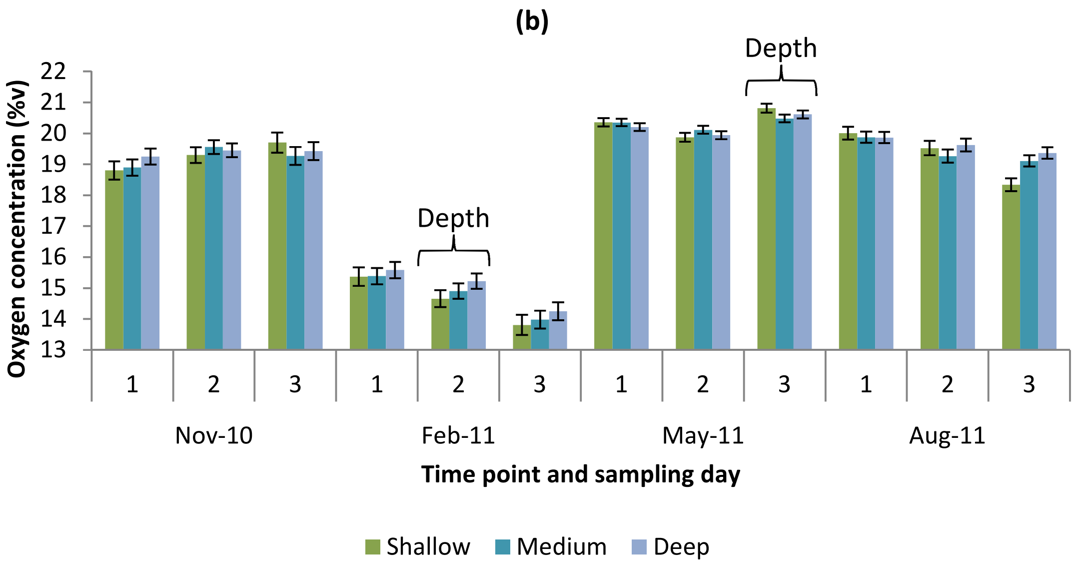


Figure 8.12 Mean oxygen concentration over both pitches at each depth on each day during each time point in the wicket location (a) and centre (b). Vertical bars denote standard error. Days when there is a significant difference between depths are marked.

8.4.6 Carbon dioxide

The response of carbon dioxide was generally the inverse of oxygen concentration, i.e. when oxygen decreased, carbon dioxide increased. Crucially there were no differences between the aerated and control pitch in carbon dioxide concentrations (Figure 8.13).

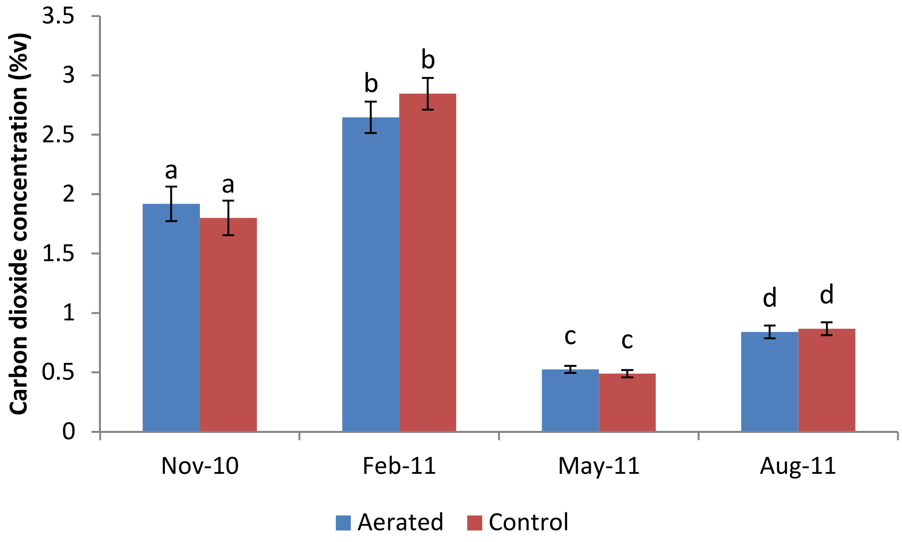


Figure 8.13 Mean carbon dioxide concentration over all depths and locations for the aerated and control pitches. Vertical bars denote standard error. Letters indicate homogenous groups at p<0.05.

There were differences between locations but these were independent of aeration and only present in Feb-11 (Figure 8.14)

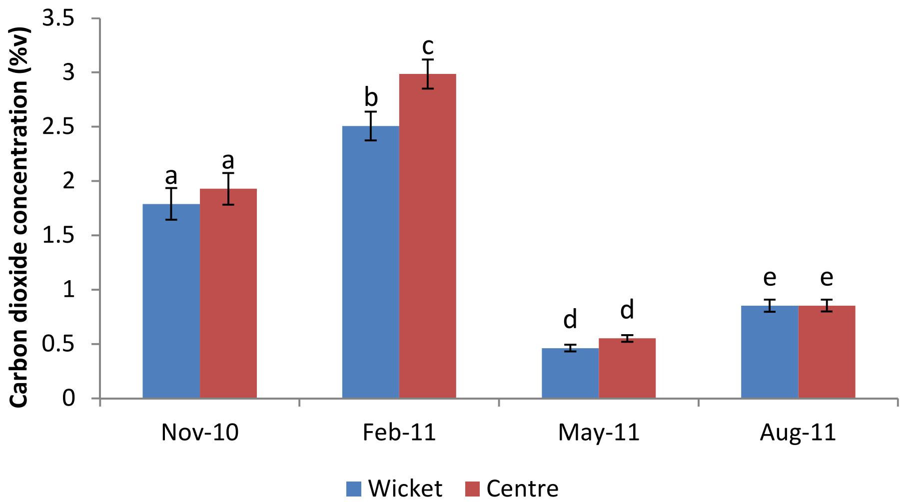


Figure 8.14 Mean carbon dioxide concentration over all depths and pitches for the wicket and centre locations. Vertical bars denote standard error. Letters indicate homogenous groups at p<0.05.

8.4.7 Oxygen and carbon dioxide

A model was created using the carbon dioxide concentration and oxygen concentration from every tube array, depth and time point (Table 8.8).

Table 8.8 Multiple regression model for carbon dioxide concentrations (%v). Explanatory variable is oxygen concentration (%v). b* is the standardised regression coefficient, b is the regression coefficient.

Explanatory variables	b*	Std.Err.	b	Std.Err.	t(425)	p-value
Intercept			8.72	0.212	41.2	<0.01
Oxygen concentration	-0.857	0.025	-0.387	0.011	-34.2	<0.01

Summary statistics	
Multiple R	0.86
Multiple R^2	0.73
Adjusted R^2	0.73
F(2,322)	1173
p	0
Std.Err. of Estimate	0.480

The model explained 73% of the variation in carbon dioxide found and was significant at p<0.05.

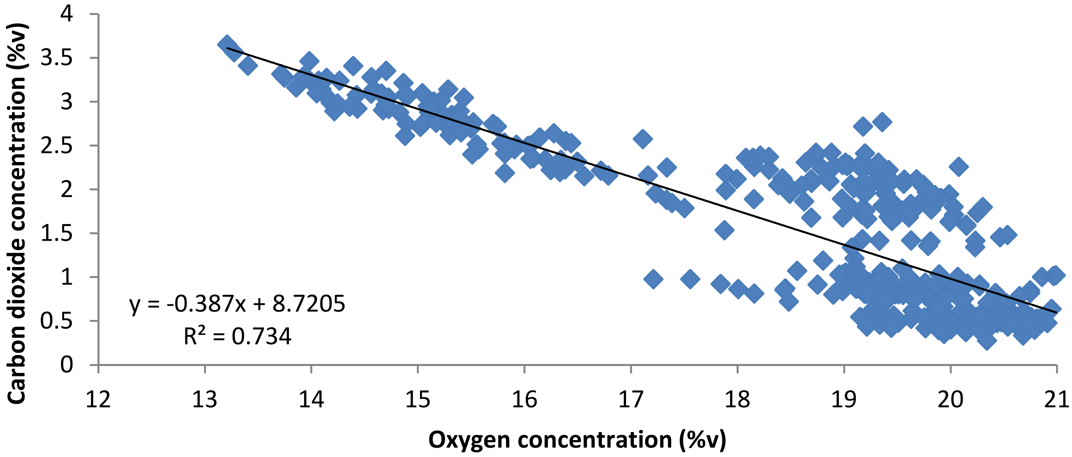


Figure 8.15 Plot of carbon dioxide concentrations against oxygen concentrations.

8.5 Discussion

The data from August 2010 shows the two pitches were not significantly different before any aeration treatments were applied and can be used as a fair comparison for the effects of treatment without the need to compensate for any inherent differences.

Throughout the results there is a clear effect of rainfall on the oxygen concentrations in the soil, first manifesting on Day 2 in August 2010 but also visible at several points throughout the remaining months, most noticeably in February 2011.Reports (DeSutter *et al.*, 2008b; Chong *et al.*, 2004) indicate increased carbon dioxide with increased water content, and decreased oxygen concentration (Stępniewski and Gliński, 1985; Simojoki *et al.*, 1991; Jiang, 2008). Simojoki *et al.* (1991) found a close correlation between water content, rainfall and variations in oxygen concentration. There are two ways in which water affects the soil atmosphere and both are related to the extremely slow diffusion of gases through liquids compared to gases (Section 2). The greater the water content of the soil the more of the pore space will be filled with water rather than gases thereby making less of the pore network available for diffusion and the transport of gases in and out of the soil. Eventually a point is reached where the water content is sufficiently high that the pore network connectivity is diminished and tortuosity is so great that the diffusion of gases is practically zero (Stępniewski and Gliński, 1985). The second process is very similar and occurs after intense rainfall so that a layer of water percolating through the soil essentially acts as a barrier to diffusion until such time as the pressure of air trapped beneath the water layer is sufficient to burst through or the layer disperses through the pore network and is broken down reconnecting the soil to the atmosphere (Taboada *et al.*, 2001b). In February 2011 both of these effects are likely to have occurred resulting in the depletion of oxygen and the increase in carbon dioxide observed.

August 2011, despite having the same water content, showed slightly reduced oxygen concentrations relative to May 2011. The difference between the two times could be due to the elevated temperature in August relative to May which increased the respiratory demand for oxygen but also due to a period of heavy rainfall two days before sampling or a combinations of the two.

November 2010 shows very similar oxygen concentrations to those of August 2011 and May 2011 despite a much greater water content which from February 2011 would indicate a potential restriction on gas diffusion. It is possible that the water content in November 2011 had not reached a critical point whereby the blockage of the pore network was sufficient to reduce oxygen diffusion supply to levels below the demand for oxygen. The weather in November was extremely cold and the ground was blanketed with snow for the entire sampling period. The extremely low temperature in November 2011 could have reduced respiration within the soil to such an extent that the oxygen demand was very low. The elevated levels of carbon dioxide within the soil would indicate that gas exchange with the atmosphere was restricted at this time. Given the build-up of carbon dioxide without an associated decrease in oxygen concentration as seen in February 2011 would indicate an anaerobic source potentially from deeper within the soil profile where the temperature would be warmer.

Differences with depth show the shallowest tube set is generally greater in oxygen concentration than the deeper tubes. This is not surprising given that any water fronts will pass this tube first and the closer proximity to the surface will allow for the recovery of oxygen concentrations much more quickly.

Aeration only appears to affect the Wicket location with no observed difference in the Centre location between the aerated and control pitches. These differences first manifested in February 2011 prior to any game play on the pitches and therefore cannot be related to different wear patterns in the two locations. The differences may be caused by management effects however, such as the turning of the mowers or not rolling the whole roller off the pitch so the end point is only compacted by a single drum on the roller rather than two resulting in different levels of compaction in each area. Aeration increased the oxygen concentration in Wicket location very slightly as expected from Section 5 where VOST aeration was shown to increase the rate of oxygen diffusion into the soil. Morhard and Kleisinger (2004) found in a sandy football pitch that hollow tine aeration increased the oxygen concentration of the soil for a period of ten weeks, but after 25 weeks the aerated area had a lower oxygen concentration than the control. The aeration treatment had the calculated effect of creating macropores relative to total volume (to 200 mm depth) of 0.8%. The effect on surface area is far more profound and increased 88%. As such the effective surface area for diffusion is greatly increased as well as the evaporative surface area for reducing water content as in Section 7. There was no detectable difference in water content (0-100 mm) between the aerated and control pitch as measured by the theta probe.

No aeration effects were observed in months that did not include considerable rainfall in the week preceding sampling. Outside of these times the control pitch was the same as the aerated so that in the field it may be the effect of aeration on hydraulic conductivity rather than increased macroporosity that is of benefit. However, the increased diffusion from the large macropores would be of even more importance when the water content of the soil was greater. Two possibilities present themselves:

1. the macropores speed the movement of water through the profile and increase evaporation allowing an increase in air-filled porosity more quickly following a period of rainfall
2. the increased diffusion rate from aeration is only noticeable over the natural rate following a rainfall event and subsequent increase in localised water-filled porosity.

There is insufficient data to be able to discern clearly which theory is right. If VOST aeration increased the speed with which water layers restricting access to the atmosphere are dispersed then it would be expected that the aerated pitch would show a much faster recovery to pre-rainfall oxygen levels than the control. If the increased diffusion rate is correct then it would be expected that the pitches would recover at a similar rate, as the water layer is dispersed over the same time period, but the oxygen concentration in the aerated pitch would remain slightly greater than in the control pitch over the period due to increased diffusion rate. Given the limited range in time of sampling in relation to rainfall events it is impossible to tell which theory is correct (or neither).

It is unclear why the Wicket should exhibit an aeration effect but the Centre does not. Wear and compaction from payer surface interactions would be expected to be much greater in the Wicket area than the Centre due to the nature of the game such that both the bowler and batsmen’s activities are focused here, however differences were apparent before any game play. In August 2010 following the rain on Day 2 there was a significant difference between locations in the aerated pitch and control pitch; the aerated pitch showed a greater oxygen concentration in the Centre than the Wicket prior to aeration, the opposite of that which is observed following aeration. Possibly the aeration treatment has actually done more damage to the soil at the Centre than good as was seen in Section 7 but then it would be expected to have a lower oxygen concentration across all time points after treatment which it does not. Similarly, if the difference was due to the orientation and location of the pitches a consistent observed trend would be expected, which was not found.

The lowest recorded oxygen concentration was 13%v and the highest recorded carbon dioxide level was 2.5%. These were seen only during February 2011 which had the greatest water content and the most amount of rain immediately before and during sampling. Without knowing the amount of time that the oxygen and carbon dioxide concentrations remained at these points it is difficult to speculate on exactly how much damage is done to the grass plant at these times particularly as the plant will be relatively dormant during the coldest periods of the year. (Bunnell *et al.*, 2002) determined that carbon dioxide concentrations of over 2.5% caused a significant reduction in root length and root density for creeping bentgrass and that concentrations of 10% or more had a visibly deleterious effect on turfgrass quality. The recorded carbon dioxide level did not exceed 2.5%. No information could be found on a limiting concentration of oxygen in the soil and with limited information on the time at which the plants remained at the low oxygen concentrations it is unclear whether a transitory or more long term response from the plant would be required to cope with conditions. Zabalza *et al.* (2009) found in pea roots that the plant could temporarily reduce its respiration rate to cope with temporary low oxygen environments. Jiang (2008) reported two studies, one in maize and one in wheat, that found the formation of aerencheyma in root tissues exposed to long periods of low oxygen stress. It cannot be said that the oxygen concentration in these pitches was so low as to be damaging to the plant however it can be clearly shown that aeration did increase the oxygen concentration compared to the control.

In a well aerated soil the carbon dioxide increases should follow a 1:1 relationship with oxygen content decreases (Stępniewski and Gliński, 1985; Simojoki *et al.*, 1991). The measured relationship here was approximately 1:0.4 oxygen decrease:carbon dioxide increase. In a wet soil the increased solubility of carbon dioxide in water relative to oxygen tends to distort the relationship resulting in a ratio of less than one. Due to the nature of the experiment here where the reduced oxygen concentration and increased carbon dioxide particularly at the extreme end of the range measured was caused by rainfall and high water content the solubility of carbon dioxide is likely to be a significant factor.

8.5.1 Method limitations and suggestions for future work

Ideally more pitches would have been monitored to ensure that it was not individual pitch characteristics influencing the results i.e. that it is on the basis of the location of the pitch, either Wicket or Centre, that is the cause of the changing aeration effect rather than just a factor of the location in that particular pitch.

Observations over a longer period of time would not only observe the development of the pitch over time with increasing amount of games and the additive compaction of the roller from year to year but also allow comparisons in time as to the effects observed.

The variation observed here and the dependence on immediate weather conditions requires continuous monitoring rather than spot checks throughout the year in order to gain a full understanding of the dynamic interaction of the oxygen concentration with temperature and rainfall fluctuations. In order to achieve this it is recommended that the system be altered to use gas sensors instead of gas chromatography as the main method of analysis. No trace gases were detected and oxygen and carbon dioxide sensors represent a cheap and effective method of monitoring the gaseous concentrations with high frequency in time. The ability to automate the process using gas sensors would relieve the compromise between sampling frequency and analysis time. A fully automated system with automatic valve switches connecting all the tubes to a centralised set of gas analysers would allow user-independent data logging all year round sampling as frequently as desired. Potentially to reduce the volume of tubing outside of the porous collection tube each tube array should have its own set of automated sampling equipment.

Little was known about the distribution of gases in a cricket pitch with depth when the system was designed. As such the depths of sampling chosen did not span sufficient distance to show an independent result effectively resulting in a replicate of nine for each pitch location rather than three depths of three replications. Ideally the tubes would have been separated by a greater distance to elucidate a concentration distance curve to gain greater detail on the effectiveness of aeration in increasing gas exchange to greater depths and the potential implications on rooting activity.

The 250 ml sampling chamber could potentially be removed from the system as the 5 mm PVC tubing presents sufficient damping on the action of the pump to ensure that a smooth and steady flow is achieved through the porous tubing. This would minimise the volume of gas outside of the porous tube and provide a more accurate representation of the gas within the porous tube. Sampling could be achieved by inserting a three-way connector in place of the sampling chamber, one end of which is fitted with a rubber septum for sample collection.

Only VOST were examined using only one treatment regimen leaving scope for the examination of a range of other aeration techniques and alternative application frequencies, timings and depths.

8.6 Conclusions & relevance to cricket

A clear increase in oxygen concentration was seen in some areas of the pitch but not others as a result of VOST aeration. No clear reason could be discerned as to why the treatment was ineffective in one region of the pitch compared to another. As in Section 7 the effects of VOST aeration are erratic and prevent a definitive conclusion of an unambiguous benefit from application. VOST aeration did not negatively influence the oxygen concentration or the carbon dioxide concentration in the Centre, in fact it seemed unaffected by it mirroring the control pitch.

This experiment seems to highlight the leading conclusion from many other experiments that aeration is generally only necessary if the pitch is in some way damaged or distressed. In this case it became clearly evident that VOST aeration only confers a benefit when the pitch is exposed to more extreme situations such as heavy rainfall on an already wet soil. The pitches here are newly laid, with fresh soil and suffer none of the problems of layering. The oxygen concentration never fell drastically low, nor did the carbon dioxide concentration become distressingly high. In a layered pitch the potential for pitch distress from rainfall and high water content are much more likely. The drainage problems presented by both a horizontal break or a compacted layer will tend to exacerbate the problem by creating a perched water table or physically barring the movement of water respectively. In either case the potential for the pore network to become water-filled beyond the critical level of air-filled porosity required to maintain sufficient gas exchange is increasingly likely and the resulting anoxic and high carbon dioxide conditions will deter the growth of roots.

As always the knowledge of the profile structure is key when deciding on an effective aeration treatment. If the profile contains breaks of layering then aeration to a depth exceeding that of the layer may help to aid hydraulic conductivity and provide conduits for improved gas exchange. If the profile is clean then a consideration of the particular soil must be considered, if like Soil K in Section 7 it has a high sand content and can successfully remove water through its existing pore network then aeration may be of less benefit than a finer-textured soil where aeration has been shown to decrease water content and so there is a two-fold benefit of increased air-filled porosity as well as conduits for increased gas exchange. Finally the climate and natural over-winter state of the pitch must be considered, if rainfall is high and frequent or the pitch remains wet and undraining throughout then VOST aeration would be of benefit. If there is little rainfall and pitch drains well then once again aeration would seem to confer little additional benefit.

Only VOST aeration is examined here but there seems no logical reason why similar treatments such as Air Injection and Deep Drill (Section 7) would not confer the same benefits. The Deep Drill may actually be more effective as the treatment causes less compaction around the tine when it penetrates as the technique bores into the soil rather than thrusts so the soil is removed and not compressed. As such the pore network surrounding the drilled holes may be capable of greater gas diffusion and exchange than the compacted soil around a VOST created hole.

The deeper the working depth of the machine the further the oxygen can freely reach into the soil (before entering the restrictive soil pore network) and the greater the surface area of the soil is available for gas exchange. In theory then the deeper the aeration treatment, the more effective it will be at increasing oxygen concentrations and decreasing carbon dioxide to a greater depth. When using VOST the level of compaction will increase the deeper the tine penetrates as more soil is displaced. Hence there must come a point where the gain in depth is offset by the increased compaction. No such restriction should apply to the deep drill. The choice of tine type may be of critical importance here. Using star-tines that have a small overall volume of tine hole but a large surface area may be the key for creating a larger area for gas exchange whilst minimising compaction and may improve the effectiveness of VOST treatments.

To summarise VOST aeration has been shown to be effective at increasing oxygen concentrations but as always care must be taken to ensure that treatment is necessary and that it will be effective. Opportunities exist to increase the potential effectiveness of the VOST technique for gas exchange by moving to tine types that maximise surface area creation for the minimum volume and thus reduce compaction potentially allowing for deeper working depths with greater benefits than could be achieved with traditional cylindrical tines.

9 Research Synthesis & Interim Guidelines

9.1 Research synthesis

The aeration survey revealed the broad range of expectations that groundsmen have for the effects of aeration on their pitches which contrasts with the evidenced actions of aeration from the experiments here.

Two purposes for aeration in cricket pitches were identified. One was as routine preventative or beneficial treatment and the other was as a curative treatment for root breaks and layering. The primary focus of the research was centred on aeration as a routine treatments due to the lack of layering present in the relatively recently constructed test areas though the results of some experiments were considered in light of the potential benefits in a layered system.

The soil is a highly interdependent system and what effects one factor often has has secondary effects in other areas. This section aims to bring together the research from the five experiments and the insights of the aeration practices survey to provide a holistic overview of the effects of aeration and its relevance to cricket groundsmen in their application of it.

9.1.1 Aeration treatments as a routine treatment

The vertically operated solid tine (VOST) dominates as the treatment of choice for both routine and curative treatments. VOST was shown in the laboratory and in the field to positively increase the oxygen concentrations in the soil and increase the rate of oxygen diffusion into the pore network. It was found in the field that the benefit of VOST in increasing oxygen concentrations was only apparent under the more extreme conditions in the soil (high water content and low temperatures) and was highly dependent on weather conditions, particularly rainfall and to a relatively smaller extent on temperature. This effect was not universal throughout the entire area of the pitch and no clear reason was determined for this. Field trials examining the effect of VOST on the physical properties of the soil found it to be sporadic in its effects and variable, sometimes causing a positive effect and sometimes causing a negative effect.

With this in mind it is not entirely surprising that the entire pitch does not respond positively to VOST in other ways. VOST consistently demonstrated increased oxygen diffusion into the soil in the laboratory and showed some improvements in the field. Overall it is clear that aeration should in general increase oxygen concentrations and that it does so for extended periods of time; for example a treatment applied in November retained a significant effect on the soil through to August the following year during field trials in Section 8. Examination of the soil profiles from the aeration trials revealed that the tine holes can persist below the surface of the soil for up to seven months which may explain the long term effect observed.

The increased gas exchange from VOST and potentially other aeration treatments could be due to the huge increases in surface area that are created. This was shown in the smaller average pore sized Soil O to decrease water content as a consequence. A decreased water content would benefit soil gas diffusion as more of the pore space would be air-filled and thus available as part of the gas transport network, increasing connectivity and decreasing tortuosity improving overall exchange capability. Even a small change of 3%m water content was shown to drastically increase the rate of oxygen diffusion through the soil. VOST was demonstrated in the laboratory to increase the rate of oxygen diffusion into the soil regardless of water content, which when coupled with an additional ability to lower water content, the total improvement in diffusion capability may be of significant benefit.

Aeration was found to be soil type dependent in its effectiveness. Water content reduction was only found in soil with a smaller average pore size. Soil K with a larger average pore size appeared to have no benefit from increased surface area in decreasing water content beyond the soil's inherent capability. There is still the potential for the increased oxygen diffusion demonstrated from the laboratory trials, regardless of water effects, so aeration of soils similar to Soil K with a larger average pore size may still be beneficial although the larger average pore size may mean they are already sufficiently capable of supporting sufficient gas exchange to maintain life supporting oxygen concentrations at depth.

Both the water content reduction and the increase in oxygen diffusion are related primarily to the increase in surface area of the soil and the working depth. As such it was suggested that moving away from the traditional cylindrical shaped tine to a fluted star shaped tine would reduce the compaction of the soil by virtue of the smaller volume whilst increasing the gain in surface area; however, this was not examined experimentally.

It was expected as a consequence of increased oxygen concentrations that the microbial population would increase and the breakdown of organic matter would rise as a result of it. This was not the case as all five aeration treatments examined in the field trials showed no effect over that of the control. It was found that a good maintenance regime involving regular scarification was more effective at reducing organic matter content. This is particularly important if the groundsman has been successful in consolidating the pitch to a high bulk density. The effect of greater bulk density was to increase significantly the root density in the upper layers of the profile with a consequent decrease at depth, but with no overall decline in total root mass. This corresponds to a huge increase in organic matter in the upper layers of the soil which will rapidly form a soft spongy layer, destroying the hard work of pitch compaction and resulting in a poorly performing pitch. As such, regular deep scarification/linear aeration is vital as aeration alone will not be effective at removing or facilitating the breakdown of this organic matter. If not contained the rising organic matter content may necessitate the removal of soil through fraise mowing and replacement with fresh loam – a much more expensive operation than scarification. A balance must be reached between achieving a high enough bulk density for a good game of cricket, but not too high so that the pitch becomes unmanageable. Potentially groundsmen will become a victim of their own success if they aim solely to increase bulk density at the expense of everything else. Not only does a high bulk density cause shallow rooting but it also decreases infiltration and hydraulic conductivity, increases tortuosity and decreases connectivity of the pore network, and as such is more prone to anoxic conditions. Such a pitch would very quickly go from a hard, fast paced pitch to a poor quality, high organic matter, substandard playing surface. VOST was shown in pot experiments to increase root density but this was primarily due to growth of roots within the tine hole and did not increase root depth. Aeration is not the answer to gaining deep roots in a high density soil. A careful balance must be achieved between sufficient bulk density to achieve a good ball-surface interaction with the awareness that very high bulk densities will significantly increase thatch development.

This is particularly important given that in field trials and pot experiments aeration did not decrease the bulk density of the soil. The increased surface area from aeration has been shown to decrease water content due to increased evaporation. It would be expected that an aerated soil go through greater shrink-swell cycles as the soil will start from a drier state and dry more quickly than a non-aerated soil and thus expand and contract to a greater magnitude and speed. The greater extent of shrink-swell in aerated soils would then lead to decreased soil bulk density. This was not the case. Clearly the small amount of additional evaporation was not sufficient to lend significant effect over the control plots. Most aeration treatments compress the soil as the tine is thrust into the soil as such many benefits from aeration may be lost undoing the compaction created by the treatment. There is a large annual variation in density due to prevailing weather conditions through the year and its resulting effect on soil water, both content and state (liquid or solid). Aeration does not have any effect on these seasonal variations. The generally wet autumn and winters lead to a swelling of the soil and a subsequent reduction in bulk density. The generally dryer, and warmer, late spring and summer leads to a reduction in soil water content, shrinking of the soil and an increase in bulk density. The effect of the seasons dominates over any aeration effects on the physical properties of the soil and it is these processes on which groundsmen must rely on to relieve the compaction in the pitches from rolling, not aeration.

As a routine application groundsmen must consider carefully why they are applying aeration. Two key effects are noted here:

1. Reduced water content (soil type dependent)
2. Increased oxygen availability

Outside of these two effects, aeration in a non-layered profile appears to give little additional benefit. Equally, no long term damage was found from treatment application although the potential for building up a compacted layer from repeated treatments was postulated. If the pitch is constructed from a soil with a small average pore radius similar to Soil O then routine application with solid tines would be beneficial in reducing water content and increasing gas exchange as a result. If the pitch is constructed from soil with a larger average pore radius then aeration would seem to be of little benefit but may slightly increase gas exchange if applied. If the grass is healthy and shows no signs of stress and examination of the profile reveals no signs of anoxic conditions or layering then aeration would seem to be unnecessary. If however the grass shows signs of stress potentially from a low oxygen environment in the soil, and examination of the profile reveals symptoms of anoxic conditions then aeration may well be of considerable benefit.

9.1.2 Aeration treatments as a curative treatment

Fifty-four per cent of respondents to the survey reported root breaks or layering within the profiles of their pitches and almost all were using some form of aeration to try and remove them. The treatment of choice was primarily VOST followed by the Deep Drill. Clearly root breaks and layering represent a considerable problem to cricket at all levels of the game (the First Class facilities reporting the highest incidence, though this may be because of increased awareness at this level).

Although not targeted directly in the experiments some conclusions and hypotheses can be considered in light of the research findings.

In the same way that roots grow preferentially down the tine holes they will also grow laterally along a horizontal break along the path of least resistance. The current practise on attempting to solve a horizontal break is to use either VOST or Deep Drill aeration to a working depth below that of the break, and backfilling with a suitable soil in the hope that roots will grow down the tine holes and bind the pitch together. In the Section 6 the roots formed a mass in the tine hole but did not grow out of the tine hole which may limit the effectiveness of this technique, particularly if the underlying soil is very dense. This technique was applied to a pitch with a root break and did appear to show an improvement with repeated annual applications (Woods, 2012). The necessity for repeated applications stems from the fact that the cross-sectional area of the newly formed channels for root growth account for only 0.5-2% of the total area for each application (depending on treatment choice). Repeated applications will be required to build up sufficient aggregate effect. Applying a greater annual frequency of the treatment to try and increase the effectiveness could be of benefit but has to be balanced with the time taken to backfill the holes (which has to be done by hand) and the resultant costs of treatment and remediation. Essentially what this technique is doing is gradually replacing the incompatible soil with a more suitable loam that will bind to the underlying soil. Depending on the depth of the break it may be more cost effective to Fraise mow to the depth of the break removing completely the incompatible soil and replace it with fresh soil that will be compatible and bind to the underlying layer, rather than repeated applications of deep penetrating VOST or Deep Drill over a period of years and subsequent backfilling, particularly as the Deep Drill can only be hired. The added benefit of complete replacement is that the problem should be completely cured rather than the aeration solution which is more of a repair patch than a cure. This must all be balanced with the severity of the problem, the expected downtime from Fraise mow replacement and the depth of the problem, obviously the deeper it is the more expensive in resources and the longer it will take to get the pitches back to full capability. Given that in New Zealand a similar treatment of Fraise mowing the pitches is applied annually (Carter, 2012) this represents a suitable method for quickly and completely curing a horizontal break in a pitch (at a shallow depth at least) without any loss of playing time.

In Section 5 a compacted layer of soil had a profound effect on the diffusion of oxygen through the soil. A compacted layer is a physical barrier in two ways; firstly the pore network in this region is likely to have a small average pore radius with high tortuosity and low connectivity and as such will restrict gas diffusion. Secondly, this area will have a greater degree of saturation at a lower gravimetric water content than a less compacted soil and so water filled pores and water films are going to restrict gas diffusion even further. The compacted layer will also likely restrict water movement through the soil and so the soil above is likely to become saturated more quickly and drain less efficiently. Similarly a horizontal break will create a perched water table raising the water content of the soil above it. Water content was shown to have an inverse relationship with the rate of gas diffusion through the soil; so high water content, for whichever reason, is more likely to generate a low oxygen environment that stresses the plant and restricts root growth. Aeration has been shown to reduce water content by increasing the surface area of the soil and VOST has been shown to increase oxygen concentrations both of which would be of benefit in these situations. The use of the Deep Drill was hypothesised to provide similar benefits to VOST in increasing gas exchange and could potentially be better due to the reduced compaction around the tine hole walls from this treatment unfortunately this hypothesis was never tested, though it could be easily done using X-ray CT scanning (Petrovic, 1979). Aeration with working depths that can penetrate the compacted layer or horizontal break would provide further benefits, more so in the case of the compacted layer as they provide a direct connection between the free atmosphere and the soil below it by bypassing the physical restrictions of the compacted layer.

If the layering problem in the pitch is created by a buried thatch layer then aeration has been shown not to effect organic matter content or microbial populations and the only viable solutions appears to be to replace the soil to the depth of the problem.

The curative application of aeration to layered pitches was considered in light of the research findings. When choosing an aeration treatment for these situations groundsmen must consider the nature of the problem they are facing and the resources they have available. If there is a horizontal break in the pitch the root cause must be determined, whether it is a buried thatch layer or incompatible topdressing, and careful consideration of the time taken to effect a solution from VOST or Deep Drill applications compared to Fraise mowing made. In situations where the break or layering is restricting water movement through the soil, VOST and Deep Drill aeration would be beneficial in relieving the stress of a low oxygen environment, as well as potentially encouraging deep rooting.

9.1.3 Key contributions to knowledge

The overall contribution to knowledge provided by this research is the quantified effects of a range of aeration treatments in fine-textured soil. Previous to this study little or no research into aeration on fine-textured soils was found by the author. Previous research is dominated by applications to golf courses primarily based in sandy soils and generally focused on hollow tines and solid tines.

New methods were developed to study the dynamic interactions between expanding clay minerals and water. Both methods utilised time-lapse photography to record the expansion and contraction of the soil. The expansion method was compared to a standard method and found to be highly accurate (average difference between the two methods was 0.33%) as well as providing informative time-series data on the nature of soil swelling in five different soils. The method for assessing soil shrinkage was more challenging and there remains some additional improvement to fully leverage the capabilities of this technique. The use of time-lapse photography allowed high time-resolution analysis of how these dynamic processes change with respect to time and among different soils in relation to pore size and clay content.

A survey of the industry was conducted to capture the attitudes to aeration of cricket groundsmen across the UK at all levels of the game. The survey captured information on equipment use, autumn maintenance regimes and current beliefs on the benefits of aeration on cricket pitches. The survey also detailed information on the prevalence of root breaks and layering in pitches highlighting the severity of the problem facing the industry. The survey provides not only an informative guide on how best to focus the guidelines to improve best practice but also a snapshot in history so that future studies can use it as a comparison to assess the impact of future guidelines or how treatments in the past may have impacted pitches in the future. It is believed that this is the first time such a survey has been undertaken to examine cricket aeration practices.

Previous research into the effect of soil dry bulk density on root density and microbial biomass was used as the basis for developing a method to examine the additional effect of aeration with changing bulk density which had not previously been examined in a clay dominated soil.

A range of equipment was examined for its effect on the physical and biological properties in two different clay loams. The study evaluated the immediate and long term effects of the techniques and compared them to previous research in sandy soils. Overall the effectiveness of each technique appeared to be diminished in comparison to sandy soils with few noticeable effects due to the background effects of shrink-swell in clay minerals.

Studies of the soil atmosphere have primarily been conducted in agricultural systems and required the adaption and development of a new method successfully to construct a sampling system in two fully useable cricket pitches to enable the study of aeration and its effect on the soil in as realistic a setting as possible. This represents the first application of a closed-loop sub-surface system used to examine the soil atmosphere under a playable sports surface and its response to aeration. Together with laboratory studies in the same soil, aeration was shown to increase significantly oxygen concentration in the soil for up to nine months.

9.1.4 Limitations of the study and future recommendations

Each chapter detailing an experimental method features its own discussion on the limitations of the individual experiment. This section examines the wider aspects limiting the overall study and suggestions for future work.

The wide range of expectations that groundsmen have about aeration required a broad range of evaluation criteria to examine the effectiveness of aeration. It was identified early on that there were two general uses for aeration, as a routine and as a curative treatment. Limitations in time and resources required the work to focus on only one of these aspects and the availability of existing test areas suitable for examination of aeration as a routine treatment made it the logical choice. Given the prevalence of root breaks and layering in cricket pitches across the country it is unfortunate from the viewpoint of producing guidelines that more information regarding aeration as a curative treatment could not be determined and would require at least another four years of research particularly regarding the pinning together of horizontal breaks which is a process that takes years to accomplish.

The wide ranging expectations on aeration required a wide range of tests to characterise fully and answer the questions surrounding the technique in cricket pitches. As such the work is spread over a broad range of criteria and required compromises in terms of the amount of detail and the range of techniques that could be examined. While five techniques were examined for the effect of physical and biological properties on the soil, only VOST was examined in the laboratory and field gas diffusion experiments and also in the root density experiments, leaving scope for the full range of aeration treatments to be tested in this manner. The treatment was only applied at one frequency (i.e. one application in the laboratory experiments, twice in the field trials) and so it is not possible examine the question of whether the treatments were not being applied enough (or too much) to effect a change (or damage).

Similarly while two different soils were studied in field trials examining the effect of physical and biological properties on the soil, only one soil was used for the remainder of the work, except the shrink-swell time-lapse methods. Previous work (Shipton, 2008) has shown considerable variation between the behaviour of different clay loams, which was also seen in the field trials and shrink-swell laboratory experiments. As such work remains to examine the effect of aeration in different soils regarding its diffusion and root growth characteristics.

Finally the effect of aeration of the hydraulic conductivity and infiltration rate of the soil was not determined and may play a critical role given the close relationship between water content and gas diffusion in the soil.

9.2 Interim guidelines

The taking of a soil core is essential to determine the correct course of action when deciding on an aeration treatment. An aeration decision pathway for recommending an appropriate aeration treatment is presented in Figure 9.1. If the soil core presents with horizontal breaks or layering, then the curative pathway should be followed (Section 9.2.2). If there is no sign of layering or breaks the routine pathway should be followed (Section 9.2.1).

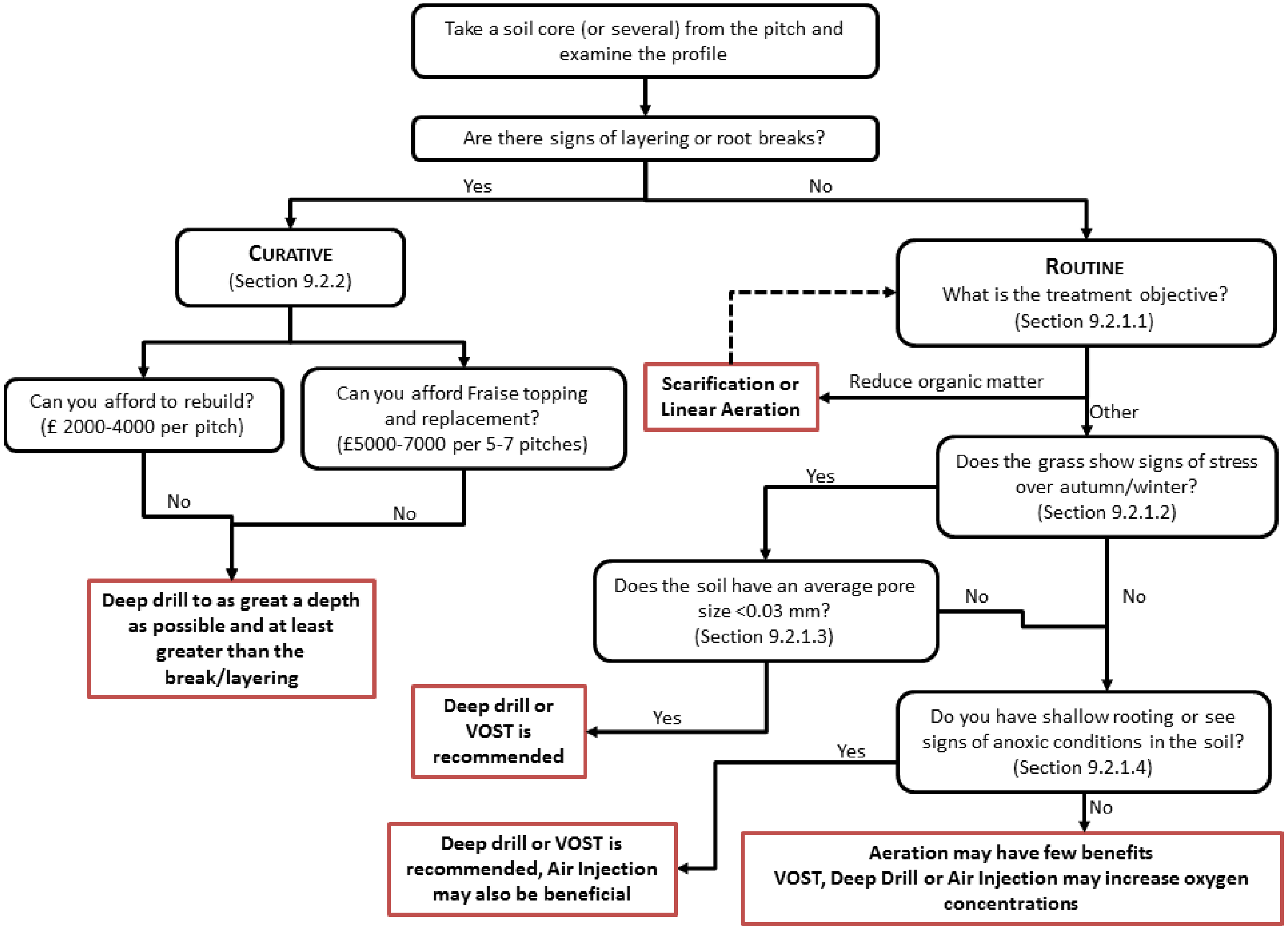


Figure 9.1 Aeration decision framework

9.2.1 Routine

9.2.1.1 What is the treatment objective?

When embarking on an aeration programme careful consideration of what the intended aim for improvement is and which treatment is best to suited to achieve this.

High bulk density soils have been shown to increase the root density near the surface which may cause an accumulation of organic matter in the upper layers of the soil. None of the aeration treatments testing showed the capability to remove or reduce the organic matter content of the soil beyond that achieved by scarification in the autumn. Therefore if the goal is to control organic matter content then deep scarification should be the primary treatment method.

If the objective is not to remove organic matter then it is assumed there must be other problems in the pitch which require affirmative action. Otherwise the groundsman must consider why, if there are no problems with the pitch, it is necessary to aerate at all.

9.2.1.2 Does the grass show signs of stress over autumn/winter?

If the soil profile does not show breaks or layering this does not mean that there is nothing wrong with the pitch or that aeration could not be beneficial. If the grass is showing signs of distress (e.g. yellowing of the leaves, poor resistance to disease) this could be a sign of poor gas exchange in the soil, possibly related to a high water content.

9.2.1.3 Does the soil have high clay and silt content and low sand content?

This question relates to the different properties and response to aeration of the two different soils tested. The higher clay and silt content in Soil O (30:40:30 sand:silt:clay) led to a smaller average pore radius (0.01 mm) than Soil K (47:27:25 sand:silt:clay, 0.03 mm average pore radius) which appeared to lower the soils natural capability of reducing the water content by either evapotranspiration or hydraulic conductivity. All aeration treatments tested were shown to reduce the water content in this soil and as such aeration is recommended in this soil. All of the aeration treatments tested were effective at reducing water content but the VOST and deep drill were particularly recommended as they allow for deeper penetration so increasing the surface area further and allowing deeper direct access to the free atmosphere for gas exchange. Soil K had a greater sand content and lower clay and silt content with a consequently larger average pore size and appeared to gain no benefit above the natural rate of water removal from aeration therefore aeration is not automatically recommended in this soil.

9.2.1.4 Do you have shallow rooting or see signs of anoxic conditions in the soil?

Examining the soil core once again check the soil for signs of anoxic conditions, these may include darker or black bands of soil and noxious sulphurous odours. Also check to see if the grass plant is rooting to the base of the core and if it is not assess where it stops and why. The most likely cause of shallow rooting is due to either a very high bulk density or a compacted layer of soil in the profile. Very high bulk density soils have been shown to directly cause shallow rooting. Compacted layers in the soil have been demonstrated to greatly restrict the diffusion of oxygen as well as presenting a mechanical barrier to root penetration. If anoxic conditions or shallow rooting is present then aeration using the Deep Drill or VOST is recommended to a depth greater than the anoxic zone/rooting depth. Soils with a larger average pore radius were shown to react positively to Air Injection and demonstrated the removal of a compacted layer of soil when examined in field trials. Soil with smaller average pore radii appeared to gain no benefit from Air Injection over standard VOST. VOST was shown to increase oxygen concentrations in field trials and increase the rate of oxygen influx to the soil in laboratory trials and would be of considerable benefit in these cases. The Deep Drill would possibly be even better as it may cause less compaction of the soil from treatment and so the tine holes may be more efficient at gas exchange due to the expected greater porosity around the tine holes compared to VOST. The wetter and more plastic the soil is on treatment applications however the greater the amount of smearing and side-wall compaction will occur for any treatment. Thus, aeration at the lowest possible water content at which full working depth can be achieved is recommended.

If there are no signs of shallow rooting or anoxic conditions then aeration may confer a small amount of benefit in increasing oxygen concentrations but this must be balanced against the cost of the treatment and any damage it may do to the natural soil structure so it may be that no aeration treatment is the optimum choice.

9.2.2 Curative

When examining the soil core for breaks and layering, their depth and the suitability of the soil (e.g. extent of organic matter and related soil strength) in the profile are of key importance. There are several methods available for restoring the quality of a pitch affected by breaks and layering. Option one uses Fraise topping to remove the soil up to 75 mm depth with each pass. The offending soil can subsequently be replaced, reseeded and should be available for use in the next season so offers minimum disruption (Bates, 2012; ECB Staff, 2011). The breaks in the profile must be above 75 mm for the pitch to be available the following season, work deeper than this will require a settling in period due to the increased disruption in the profile.

Several options exist for multiple breaks and layering particularly below 75 mm depth. The most expensive option would require digging up and relaying the pitch as outlined in ECB Staff (2011). An alternative is Fraise topping and cultivation, the top layer is removed, as before, down to approximately of 75-100 mm depth and the underlying soil cultivated to break up the structure and reconsolidated. This deeper treatment with the additional disruption to the underlying profile requires a longer ‘settling in’ period for the treated pitch; it is unlikely that this pitch will be available for the following season. For breaks of 75 mm depth or greater the influence of these on ball bounce is likely to become increasingly limited the further down the profile they are. Exactly at what depth the break ceases to effect ball bounce has not been quantified. The heaviest roller (1250 kg m^{-1} width of roller) in Shipton (2008) exerted a pressure of 214 kPa on the surface but diminished to zero detectable pressure at depths below 75 mm. A cricket ball weighs approximately 163 g so would consequently have to strike the surface at a very high vertical speed to exert that amount of force, calculated at 26 m s^{-1} or 59 mph (assuming a contact area of 0.04 m^{-2} and a deceleration time of 0.0001 s) well below the average vertical speed of bowlers of 7.7 m s^{-1} (James *et al*., 2005). Based on this breaks below 75 mm would be expected to have little effect on ball bounce and reconstruction would be a waste of resources.

An alternative, that does not involve disrupting the surface, utilises Deep Drill aeration. The theory behind the aeration strategy is that by backfilling the holes with fresh compatible loam together with the preferential growth of roots down these new channels the pitches will be 'nailed' together. The Deep Drill technique is generally held to be more effective (Woods, 2012) however this treatment is only available as contracted work (so it cannot be borrowed, or made available from county trailers which would be cheaper) and may be beyond the resources of many clubs as an annual treatment. The most laborious aspect of the aeration solution is that each hole must be filled and consolidated by hand so that in the summer when the soil shrinks, the filled holes do not slump and the pitch resembles a golf-ball like surface.

The depth and extent of the break or layering has direct implications on the cost of repair as the deeper the problem is, the more soil will have to be removed and replaced (direct resource cost). The depth and extent will also determine whether the pitch can be Fraise topped, Fraise topped and cultivated, or whether the whole pitch will have to be replaced. The majority of the cost is arranging and obtaining all the machinery for use, as well as labour, and the addition of cultivation to standard Fraise topping adds little to the cost of the process. The approximate costs of such processes are detailed below:

9.2.2.1 Fraise topping and fraise topping and cultivation

The cost of hiring contractors to treat 5-10 pitches is £5000-7000. Treating less than 5 pitches will cost approximately the same as the main costs involve bringing and setting up the machinery as well as labour costs. Up to 10 pitches can be treated in a day. Treating more than 10 pitches will involve additional cost in increased time as well as resource costs for soil, grass seed and fertiliser inputs as part of the process. The Fraise topping machine can be hired for £1500-2000 for a day but it requires a skilled operator to ensure a good quality result and would not include other machinery in terms of laser guided levelling, cultivation and experienced labourers.

To replace a single pitch the estimated cost is £2000-3000 for a 100 mm depth construction (i.e., 100 mm depth of soil is removed and replaced with suitable loam, graded, levelled and seeded) or £3000-4000 per pitch for a deeper construction with a gravel raft (415-425 mm depth construction).

9.2.2.2 Deep drill

The cost of hiring contractors per day is approximately £1000-1100 in which time 10-12 pitches can be treated. As with fraise topping treatments there is little reduction in cost for treating less than 10-12 pitches.

9.2.3 Summary of guidelines

These guidelines represent a broad outline of the recommendations framed by the conclusions of the experimental work. Attempts have been made to try and simplify the decision process with clear well-defined choices as to the appropriate action and explanatory notes to inform the motives behind the decisions. The guidelines are as short and simple as possible to encourage maximum uptake and ease of implementation. It is hoped that armed with this information the attitudes towards aeration can be swayed toward a more realistic outline of the capabilities of aeration in improving cricket pitch performance and prevent the inappropriate or ineffective use of this machinery wasting valuable resources.

9.3 Management considerations

The importance of the aeration research project to overall ECB strategy was determined in Section 1. Section 3 showed the range of expectations that groundsman have for aeration, several of which are not supported by the evidence presented. This presents a serious problem in that if groundsmen are suffering from a particular problem that they think will be solved by aeration, but aeration is in fact ineffective against, then the problem will persist and precious time and resources are wasted on a fruitless endeavour. Similarly, if there are no problems with the cricket pitch then aeration seems to be a discretionary choice, presenting yet another resource saving. It is in these situations that the informed guidance of a clear set of guidelines is of most importance. With a clear understanding of exactly what they can expect to achieve from aeration, grounds managers can apply the appropriate treatment to prevent or remediate problems in the pitch, whether by using aeration or another technique more appropriate to the problem; pitch quality should be improved and resources saved.

The interim guidelines presented above are designed to provide a clear decision pathway for grounds managers to follow, with clear explanations for the directions chosen. This is fundamental as it allows the guidelines to be applied in a generic situation and hence can assist all pitches and groundsmen regardless of the facility type and level.

Economic and environmental benefits from adoption of the guidelines cannot be quantified due to the indirect effects of the aeration treatments and the wide variety of situations in which aeration can be applied. If the groundsmen adopt the guidelines in full, then many will find that they need no longer aerate, similarly many will change the technique they apply. This may result in resource saving for those that no longer aerate, and pitch quality should be improved in the latter category but the direct financial and environmental benefit cannot be costed.

The aeration practices survey will provide a historical record of the industry against which the success of the guidelines can be measured in the future if a second survey is undertaken. The second survey could be highly informative as to the effectiveness of communication channels from the ECB to groundsmen at large. In the aeration practices survey it was clear that the survey failed to reach school or municipal facilities. As the survey was part distributed through ECB representatives this could indicate a section of cricket facilities that are not effectively being reached.

9.3.1 Creating change amongst groundsman

Cricket pitches can be unforgiving when it comes to making mistakes. The delicate balance that must be struck between creating a hard compacted surface and keeping the grass alive requires constant vigilance and hard work. The extent of root breaks and layering throughout the surveyed population is indicative of what can happen when mismanagement occurs and how expensive and difficult such problems can be to fix. As such the groundsmen are, as a rule, risk-averse in their management strategy, generally sticking to approaches that have been tried and have stood the test of time. This does not necessarily prevent bad management practices from occurring, the prolific use of marl (a mixture of cow dung and clay/marl sprayed over pitches between 1900-1960 making them flat with low pace and bounce but capable of heavy spin) and its associated after effects (it greatly reduced the binding strength of the soil, aiding the formation of layers) are a good example of this in that only after a significant number of years had passed did the extent of the damage become apparent. If the groundsman perceives that he is obtaining good results with his current practice then it is likely that they will be hesitant to undertake a new strategy, particularly if there is a radical departure from accepted practice, unless given iron-clad reasoning or a demonstrated efficacy, and even then some individuals will still be resistant to change. In this way they are like most social systems as described in the diffusion of innovation theory with a system norm of risk aversion, though as always some are more willing to experiment than others. Cricket groundsman can be subdivided into four main categories as in Section 3: first class, club, school and municipal facility. The response from the aeration survey provides a good indication of the connectivity of the various groundsmen categories (assuming equal apathy to completing the survey) as it was distributed down similar channels to those expected to be used for the dissemination of the guidelines; except the first class groundsmen who were targeted directly. In Section 3 the main respondents were club groundsmen, with a minority of school and no municipal facilities. The poor connectivity of the school and municipal facilities indicates a fractured social system which must be considered in the dissemination of the guidelines as how best to bridge the gaps between each of the groups.

The first class groundsmen are the top professionals. These individuals have a good standard of training and education. They generally have greater resources at their disposal with which to affect change. However consequences of failure at this level are far greater, particularly financially, and so may create a proportionally larger aversion to risk. The first class groundsmen meet annually to discuss relevant issues; this provides a good point for the dissemination and discussion of new information and techniques at the top level of the game. The connectivity between the first class groundsmen and their non-professional peers however may be limited.

The club groundsman is generally a non-professional volunteer and will have varying degrees of training and knowledge and an equally varied, though possibly linked, level of resources (it is likely that a well-funded club will be able to devote more resources to training the groundsman). The consequences of failure for the club groundsman are generally limited to the individual club but equally the resources for recovery from the failure may be lacking and the consequences no less devastating to the club even if it is on a smaller scale. The club groundsmen are the most numerous and appear the most well connected. This could in part be due to voluntarily meetings, such as at regional cricket groundsman association meetings, which increase exposure to new ideas and provide a forum for discussion within localised groups, but not necessarily between the groups. The regional cricket associations were the main route through which the survey was distributed thus indicating that potentially school and municipal facility groundsman are generally not present at these meetings, those that are perhaps representing the innovators amongst these groups.

The lack of a formalised organisational structure to pass information through to every groundsman generally means that only the proactive members will be reached by the guidelines as these are the most likely to attend the meetings. This is not necessarily a disaster as those reached are likely to be in the innovator or early adopter category. The key requirement is for those members to adopt the strategy and then discuss it amongst their peers to encourage the process to reach critical mass. It is important however for the knowledge of the existence of the guidelines to be widespread though in order for the innovation-decision to begin by creating interest and discussion. For school and municipal facilities it is unclear how they are interconnected amongst themselves for information to pass between schools or between municipal facilities in order the for the guidelines to diffuse through this section of the system.

Interpersonal communication has already been highlighted as the primary influence on opinions and decisions regarding the adoption of new innovations. Outside of the first class groundsman the level of training and education may be substantially lower, making interpersonal communication even more important and scientific evidence redundant as an explanatory and influential force. It is likely that a strategy focusing on opinion leaders and demonstrated efficacy is the most effective, rather than attempting to explain the new guidelines and encourage uptake from scientific evidence. This is not to say that the information should not be available or communicated at all but it must be recognised that it is unlikely to be a persuasive argument to the majority of groundsmen when compared to the advice and opinion of their peers.

The best strategies for aiding the diffusion of the guidelines amongst groundsman will be the adoption by opinion leaders and utilisation of eager groups. The general risk averse nature of the groundsman will require an observable demonstration that the guidelines are positive and non-damaging. As such the eager groups will act as a demonstration group diminishing uncertainty as to the risk of failure of the guidelines. The opinion leaders will also act as examples but with the additional role of missionaries to spread the word. The ECB pitch advisors provide an excellent group of individuals, already respected and in an advisory role that can act as opinion leaders in this. The first class groundsmen whilst forming the elite of the system are unlikely to make good opinion leaders due to the lack of connection to the lower levels of the game and the possible aversion to adoption of new innovations due to the severe consequences of failure. The eager group could be constructed of individuals already limiting the use of aeration, if they are doing so in general agreement to the guidelines, to provide a ready present group with the evidence of years to support the guidelines recommendations.

These measures however are unlikely to reach the school and municipal facilities. The simplest solution would be to attempt to encourage members of these groups to go to the cricket groundsman association meetings thus forming communication links between the fractured system groups. The ECB Chance to Shine programme aims to get local clubs to go into school to demonstrate cricket and recruit players, so there is a communication link between clubs and schools. The Chance to Shine programme will sponsor the creation of facilities for cricket, such as playground markings, but it is unclear whether the communication links extend to school groundsman receiving any extra training or special awareness of developments in cricket pitch maintenance. Online communications, such as 'Pitchcare.org.uk' provide information and user forums for discussion that are very popular. Potentially reaching out through these channels could provide greater access to more members of the community. These forums tend to have highly influential 'super users' that provide advice and recommendations. Once again opinion leaders can play a key role in this context in providing online advice in internet forums, either on existing platforms or the creation of a new formal ECB groundsman forum in which the pitch advisors could act as specialist advisors or 'super users' themselves. Unless the 'super-users' are firmly in favour with the proposed strategy however this could equally be very damaging to the spread of the guidelines as opinion leaders can work both ways.

In summary, the system in which the guidelines are to diffuse is formed of fractured groups with potentially low inter-group communication channels and unknown, but possibly low, intra-group communication amongst the school and municipal facilities. Three main strategies for increasing adoption of the guidelines are suggested: utilising the existing group of minimal aeration pitches as an ‘eager group’, using the pitch advisers as ‘opinion leaders’ and the exploitation of internet forums as a new communication channel combined with the power of ‘opinion leaders’ within them.

9.3.2 Dissemination of the guidelines

The rolling guidelines were distributed freely online as a downloadable document. The existence of the guidelines was advertised through the ECB website and a series of presentations. Uptake of the guidelines has been good with the number of downloads estimated at 3000-4000 and the feedback generally very positive. The guideline document explains the underlying scientific evidence for each recommendation and also provides a quick overview of the guidelines themselves with no explanation for those uninterested in or unable to understand the science.

The growth of online videos, through popular websites such as youtube.com, together with increasing online availability and speed has led to the ECB moving from written documents and statements to explanatory videos and interviews. A picture says a thousand words, possibly in video form it is a law of diminishing returns, but online video presents an excellent forum for the explanation and presentation of complex ideas as well as providing visible evidence and explanatory diagrams that can explain these processes much more quickly than a written document. This is evidenced in the use of online video in the new online IOG/ECB cricket pitch maintenance course and the creation of the NatWest Pitch Doctor website which features a series of explanatory videos on basic cricket groundsmanship. It is recommended therefore that an explanatory video be prepared in addition to a written document for the dissemination of the guidelines. The video acts as both an information source and advertisement of the guidelines whilst the written guidelines provide a reference source for later use or in the field where computers and the internet may be lacking.

Like the rolling guidelines a series of presentations at the first class groundsman conference, large events like the IOG Saltex exhibition and at regional groundsman association meetings are essential to spread the awareness of the guidelines. The ECB pitch advisers must also be trained in the explanations and reasoning behind the guidelines and fully convinced of them, if they are to form convincing opinion leaders.

The ECB already has a section on their website devoted to groundsmanship, it is recommended that this section be expanded to include a discussion forum in which the ECB pitch advisers act as ‘super users’ providing advice and recommendations. The forum provides another excellent communication channel to the community at large but also particularly to the disconnected school and municipal facility groundsman that seem to be outside the current communications reach. Some programme of reaching out to these groups in addition to the forum is recommended particularly in light of the importance of grassroots cricket to overall ECB strategy.

Noticeably in the latest release of the ECB ‘Recommended guidelines for the construction, preparation and maintenance of cricket pitches at all levels of the game’ document (ECB Staff, 2011) the rolling guidelines (James and Shipton, 2009) have not been incorporated. This appears to firstly devalue the ECBs apparent backing and confidence in the rolling guidelines but also diminishes the uptake of them as users must now read two documents both containing information on rolling and decide which one is the most appropriate to follow. For slow adopters in particular, this sort of confusion will severely hamper the diffusion of the rolling guidelines. In future, ECB advisory documents should be prepared with conformity of message as a key parameter.

9.3.3 Project delivery

The project was conducted over a period of four years and five months. The initial timeline was for four years; the over run was due to circumstances beyond the control of the project, in particular personal injury to the project leader, and the departure of one supervisor in the final year.

The project was delivered within budget. The production and dissemination of the guidelines lies outside the remit of the project.

10 Conclusions

The aim of the research was to gain a fundamental understanding of the effect of aeration processes on the soil physical properties and biological health of soil-based sports surfaces. Eight key objectives were outlined in Section 2, and the conclusions are discussed in light of these.

1. *Conduct a thorough and extensive review of past and current research into soil aeration.*

Very little research into aeration outside of sandy soils used in golf courses was found with the primary focus in vertically-operated hollow tines (VOHT) and vertically-operated solid tines (VOST). Most studies found the effect of aeration to be short lived generally not longer than 10 weeks. Aeration had been shown to increase soil oxygen concentrations for up to 10 weeks but less than 25 weeks. Changes in bulk density and penetration resistance from aeration were either not found or transient. The development of a compacted layer of soil was postulated from repeated aeration to the same working depth based on compaction patterns around individual soil tines but no evidence was evident of an overall development of a pan across a wide area.

2. *Investigate and evaluate the effect of aeration on soil gas exchange through the development of a technique to reliably measure changes in soil atmosphere.*

Two experiments, a laboratory study and a field-based study were conducted to examine the effect of VOST on soil atmospheres both utilising buried porous tubing. The laboratory experiment utilised buried gas wells to monitor the non-steady-state diffusion of oxygen into an oxygen free soil. Aeration was found to significantly increase the rate of oxygen diffusion into the soil. The rate of diffusion was found to be dependent on soil water content with water content increase from 23% to 26% resulting in a reduction in the rate of oxygen diffusion of 50% at depths above 195 mm and almost zero diffusion of oxygen to depths below 195 mm after 12 days.

The field study used the same porous tubing connected via a subsurface pipe system to sampling chambers and connection for circulating the gas via a pump. The experiment was conducted on two purpose built cricket pitches fully capable of being played on which was utilised in the summer of 2011. The results showed that VOST aeration effects on the soil atmosphere were longer lived than previously reported lasting up to 10 months after treatment. VOST was found to increase the oxygen concentration in the soil atmosphere but only under certain conditions, specifically rainfall events. The effects were not universally present across the pitch with some areas unresponsive to treatment.

3. *Examine the effect of aeration on infiltration rates, moisture retention & natural wetting/drying cycles of soils.*

Attempts to measure the effect of aeration on infiltration rates were unsuccessful. Moisture content under five different aeration treatments in two different soils representative of a modern cricket pitch were examined over a 28 month period and found to have strong seasonal cycles. The effect of aeration of soil moisture content was found to be soil type dependent and linked to pore size distribution; Soil O had reduced water content relative to the control whereas Soil K was unaffected. Soil K had a larger average pore size than Soil O due to a lower clay and silt content and was thought to gain no benefit from aeration over the soils natural ability to remove water by conduction and evapotranspiration which was shown to be greater than Soil O (Shipton, 2008).

To monitor natural wetting/drying cycles, and the subsequent shrink-swell of the soil, dry bulk density was measured over the same period as water content. Like water content changes in dry bulk density were found to be seasonally dependent reaching a maximum in summer and a minimum over winter correlating with soil moisture content. None of the aeration treatments showed any effect on dry bulk density at any point.

A new method for monitoring soil swelling with time was developed using time-lapse photography to provide a record of the magnitude of swelling over a high frequency of time rather than just an end-point value provided by most techniques. Five soils were assessed using the techniques and compared to a standard method showing excellent correlation. The swelling process was found to consist of two key processes depending on pore size distributions and clay content. The first process was inflation from air entrapment as the pore space fills unevenly due to a heterogeneous pore size distribution trapping air inside smaller pores. The magnitude of expansion by this process was inversely proportional to pore size. The second process was from the hydration of clay minerals in the soil and total end-point swelling closely related to clay content. The total magnitude of swelling in the field may be more limited however due to overburden, particularly with regard to air entrapment as the process is driven by pore size and capillary rise creating pressure on entrapped air so greater external pressure will swiftly reduce this.

Soil shrinkage was also assessed using time-lapse photography and compared to the accepted standard theory regarding soil shrinkage. The aim of the experiment was to examine the cracking patterns that develop in the soil related to soil physical properties to provide a test for developing or assessing soils for use in cricket pitches where crack formation is of critical importance, where ideally small cracks only will form as large cracks results in unsafe playing characteristics. The magnitude of soil shrinkage recorded followed the standard theory of soil shrinkage. The development of the crack analysis showed that the clay fraction dominated the cracking patterns of the soil and the remaining soil components had no observable effect thus allowing for a higher sand content in cricket loams for potentially easier management without affecting the cracking characteristics.

4. *Investigate and evaluate the effect of aeration on soil mechanical parameters, particularly soil strength and surface elastic-plastic behaviour.*

Soil penetration resistance and surface rebound hardness were measured using a penetrometer and Clegg impact hammer respectively. Results showed that the immediate effects of aeration were short lived and variable as to their effect. Over a period of 28 months the penetration resistance and surface hardness were recorded every four months. Only two aeration effects were observed over this period and both were in Soil K. Both the Solid Tine and Air Injection treatments reduced surface hardness slightly over the trial period. The depth of maximum resistance in the Air Injection trials moved deeper in the profile indicating the possible removal of a compacted soil layer. The recorded aeration effects were much smaller than the variation created by seasonal changes in both cases, for example the largest alteration in surface hardness from aeration was only 7% of the change induced by reduced moisture content.

5. *Survey and analyse the effect of aeration on soil microbial activity and the biological health of the soil and plant growth.*

Soil microbial biomass and organic matter content of the soil were measured in field trials over 28 months. No aeration treatment tested was found to affect either parameter. Over the course of the trial period organic matter decreased and microbial biomass increased to a steady value which was thought to relate to a regular and effective management regime, in particular, annual scarification.

In a pot experiment, the effect of soil dry bulk density, restricted gas exchange and VOST aeration were examined on grass root density, grass shoot growth and microbial biomass. Shoot growth was found to be inversely proportional to dry bulk density, diminishing as density increased and was not affected by VOST aeration. Total root mass was not diminished by increasing bulk density but the distribution of roots was altered with increasing root density towards the surface as density increased. Microbial biomass was found to follow similar patters as root density due to the nutrient source that the roots represent to the microbial population with the greatest values nearest the surface and diminishing with depth. Microbial biomass was shown to be reduced by compaction (56% reduction in mean value over the profile from 1.2 g cm^{-3} to 1.9 g cm^{-3}) and unaffected by VOST aeration. VOST aeration was shown to slightly increase the root density at 1.90 g cm^{-3} bulk density but only at depths between 75-125 mm increasing from 0.5 kg m^{-3} in the untreated units to 1.5 kg m^{-3} in the treated units. The increase was primarily due to roots growing within the tine hole itself rather than the surrounding soil and the total rooting depth was not increased. The effect of restricted gas exchange was examined using two sets of pots, one of which was sealed at the base (Sealed) and the other which was open to gas exchange at the base (Unsealed). The only significant difference between Sealed and Unsealed units appeared at the lowest bulk density 1.20 g cm^{-3} and was primarily due to the lack of water retention in these units as water passed through without absorbance whereas in the Sealed units the water was withheld and in the greater density Unsealed units, the slow rate of water movement through the soil allowed it to be absorbed rather than draining through. In the higher bulk density soils there was no significant difference between Sealed and Unsealed units.

6. *Evaluate and assess the effectiveness of different aeration techniques and equipment in field trials using the knowledge and methods gained from 2-6.*

Five different aeration treatments were compared and assessed over a 28 month period in their effect on bulk density, water content, microbial biomass, organic matter, penetration resistance and surface hardness. Overall very few effects from aeration were noted and all of these were very small in comparison to the seasonal changes throughout the year. All the aeration treatments appeared to cause a moisture content reduction in Soil O which is related to the large increase in surface area associated with treatment. Air injection in Soil K was linked to the removal of a compacted layer of soil.

VOST was assessed for its effects on soil atmosphere and oxygen diffusion through the soil as well as root density and shoot growth with changing bulk density. Whilst only one type of aeration treatment was used, the results were used to hypothesise on the expected effectiveness of other related treatments such as Air Injection and Deep Drill. It was suggested that the Deep Drill could be more effective due to the reduced side-wall compaction in this treatment.

7. *Make recommendations to practitioners for improved effectiveness and efficiency in the treatment choice and application of aeration in cricket pitches.*

The research was summarised to give practical advice to groundsmen when making an aeration treatment choice in Section 9.2. An aeration decision framework was created to easily navigate the information and choices needed to make an informed judgement as to which aeration treatment will provide the best solution to the particular pitch problems. Each step in the framework is references to the appropriate section in the guidelines for further information and the reasoning behind the framework directions.

10.1 Publications to date

Parsons, S.P., Bartlett, M.D., James, I.T. Measuring oxygen diffusion through cricket pitch soils, in: *Proceedings of the Second International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces (STARSS)*, 21st-22nd April 2010, Loughborough, UK

Parsons, S.P., Bartlett, M.D., James, I.T. Effects of Different Aeration Techniques on Clay Soil Sports Turf Pitches, in: *Proceedings of the Second European Turfgrass Society International Conference*, 11th-14th April 2010, Angers, France.

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APPENDICES

Appendix A

1

Cricket Aeration Practices Survey

This survey is being conducted in accordance with the Data Protection Act 1998. All data will be stored as a secure database for the sole use of Cranfield University. Data will be analysed and published in aggregate with participant anonymity maintained at all times.

Cranfield UNIVERSITY

Centre for Sports Surface Technology

For the purposes of this survey a pitch refers to a single strip or wicket.

Please enter as much detail as you wish (not all questions will be appropriate to every ground). This survey will only take about 10 minutes to complete.

Name:

Address:

ECB

IOG THE INSTITUTE OF groundsmanship

Contact details: Telephone:

E-mail:

County 1st class / club / school / municipal facility Name of cricket ground managed:
(Please circle most appropriate)

How many pitches do you have? How many games per season?

What soils were your pitches originally constructed from (if known)?

Which topdressing do you use now?
(Please circle appropriate)

Ongar: Norm / Plus; Boughton: Club / County; Surrey; Kaloam; Mendip

Which topdressings have you used in the past?
(Please circle appropriate)

Ongar: Norm / Plus; Boughton: Club / County; Surrey; Kaloam; Mendip

What annual autumn renovation do you do? (Please circle all relevant)

Light Scarification | Deep Scarification (i.e. Graden) | Koro/Fraise mowing

How often do you aerate? (Please tick box)

Every year | Every 2 years | Every 3 years | Never

Other (Please specify)

Do you Koro/Fraise mow your pitches? (Please tick) Yes | If yes, how often? | No

Do you use a Sarel spiked roller or equivalent? (Please tick box) Yes | No

When do you use a Sarel spiked roller or equivalent? (Please circle all relevant)

Between large scale aeration treatments in autumn/winter | Between the end of autumn/winter aeration and the start of spring pitch preparation | Preseason during spring pitch preparation

During match preparation | Post-match renovations | Routine summer maintenance | Autumn renovations

Cricket Aeration Practices Survey

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What type of aeration equipment do you use? (Please circle/tick box)
If you use more than one type of aeration machine a second sheet is supplied.

Linear aerator/ Deep scarifier	Cam-action e.g. Vertidrain	Deep-drill	Patterson Drum	Slitter	Other (please specify)

Machine manufacturer:

Machine name:

If applicable:
Tine type:
(Please circle/tick box)

Solid	Hollow/Core	Air-injection	Drill

Tine/drill/blade diameter: Tine/drill/blade spacing:

Tine/drill/blade length:

Why did you pick this machine? (Please circle/tick box)

Only one available	Picked based on examination of a soil profile	Colleague's recommendation	Other (please specify)

Has the same aerator and tines been used for the last 3 years or longer? (Please tick) Yes If yes, how long? No

What working depth do you hope to achieve with this machine? (Please circle/tick box)

0-2.5cm (0-1 inch)	2.5-5 cm (1-2 inches)	5-7.5 cm (2-3 inches)	7.5-10 cm (3-4 inches)	10-12.5 cm (4-5 inches)	Over 12.5 cm (5 inches) (please specify)

When do you generally start end of season aeration treatments (approximate date)?

How do you decide when to start aerating? (Please circle/tick box)

Soil moisture levels	Specific date	End of playing season	Other (please specify)

How do you decide when to stop aerating? (Please circle/tick box)

Soil moisture levels	Specific date	Temperature	Other (please specify)

How often do you repeat the aeration treatment?
(Please tick box)

No repeats	Every week	Every month	Every 2 months	Other (please specify)

Cost of aerating

Does your organisation own the equipment? (Please tick box) Yes No

If not, how do you obtain it for use? (Please circle/tick relevant box)

Hire machine	Owned co-operatively	Contract out the work	Borrow machine	County/Channel 4 trailer	Other (please specify)

How much does cost influence your use of this machine:

	Strongly disagree	Please mark the number in the range that fits your feelings most	Strongly agree
I'd like to use this machine more often but it is too expensive to obtain.	1 2 3 4 5 6 7 8 9 10		
I'd like to use this machine more but it is too expensive to maintain and run.	1 2 3 4 5 6 7 8 9 10		
The man-hours involved in using this machine limits its use.	1 2 3 4 5 6 7 8 9 10		

Cranfield Cricket Aeration Practices Survey

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Layering in Pitches

Do or did any of the pitches you manage suffer from layering or horizontal root breaks? (Please tick box)

Yes		No		Don't know	

If you do not have a break in your profile or don't know then please move on to the "Views on Aeration" section below.

At what depth is the break in the soil profile? [ ]

Which aeration treatments are you using to try and solve this or which did you use to solve it? [ ]

Why do you think this will succeed? (Please circle/tick appropriate box)

Improved root depth will help hold the pitch together	Physically removing the soil and thatch and replacing it with new soil that will not layer.	Other (please specify)

Views on aeration

How did you learn about aeration? (Please circle/tick box)

Seminar	Training course	Literature	Experienced predecessor	Other (please specify)

How important do you feel aeration is for:

	Not important	Please mark the number in the range that fits your feelings most								Very important
Improving overall turf health	1	2	3	4	5	6	7	8	9	10
Improving surface drainage	1	2	3	4	5	6	7	8	9	10
Improving root depth	1	2	3	4	5	6	7	8	9	10
Thatch removal and soil improvement	1	2	3	4	5	6	7	8	9	10
Decompaction from summer	1	2	3	4	5	6	7	8	9	10
Fertiliser ingress into the soil	1	2	3	4	5	6	7	8	9	10

Why does it benefit cricket squares to aerate?

	Not important	Please mark the number in the range that fits your feelings most								Very important
Improves drainage of soil preventing waterlogging and ponding	1	2	3	4	5	6	7	8	9	10
Improves the access of roots to oxygen from the atmosphere	1	2	3	4	5	6	7	8	9	10
Improves root depth by creating less compact channels to grow down	1	2	3	4	5	6	7	8	9	10
Prevents layering or reduces the effects of layering	1	2	3	4	5	6	7	8	9	10
Removes thatch and prevents organic matter build-up	1	2	3	4	5	6	7	8	9	10

Cranfield Cricket Aeration Practices Survey Cranfield UNIVERSITY

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Any other comments about your aeration or rolling management that me be of interest
Questions regarding the completion of this form: Phone 07532 384737 or e-mail: s.p.parsons@cranfield.ac.uk. Thank you for your time in completing this survey. Please return completed form to: S. P. Parsons, Centre for Sports Surface Technology, Building 42a, Cranfield University, Cranfield, Beds. MK43 0AL

Appendix B Diffusion Coefficient of Cricket Loams

B.1 Finite difference approximation

Using Taylor's theorem the terms of a function $f(x)$ can be approximated by:

$$f(x+h) = x + \frac{h}{1!}\frac{\partial f(x)}{\partial x} + \frac{h^2}{2!}\frac{\partial^2 f(x)}{\partial x^2} + \cdots \frac{h^n}{n!}\frac{\partial^n f(x)}{\partial x^n} + R_n(x) \tag{B.1}$$

$$f(x-h) = x - \frac{h}{1!}\frac{\partial f(x)}{\partial x} + \frac{h^2}{2!}\frac{\partial^2 f(x)}{\partial x^2} \mp \cdots \frac{h^n}{n!}\frac{\partial^n f(x)}{\partial x^n} + R_n(x) \tag{B.2}$$

$(+)$ n is even; $(-)$ n is odd

B.2 Crank-Nicolson Approximation

B.2.1 Time derivative

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{5.3}$$

The Crank-Nicolson method uses the central difference at time $t_{n+\frac{1}{2}}$ for the time derivative, $h = \frac{1}{2}\Delta t$. Using a Taylor series expansion, keeping x constant:

$$C_j^{n+1} = C_j^{n+\frac{1}{2}} + \frac{\left(\frac{1}{2}\Delta t\right)}{1!}\frac{\partial C}{\partial t} + \frac{\left(\frac{1}{2}\Delta t\right)^2}{2!}\frac{\partial^2 C}{\partial t^2} + \cdots \frac{\left(\frac{1}{2}\Delta t\right)^z}{z!}\frac{\partial^z C}{\partial t^z} + R_z(C) \tag{B.3}$$

$$C_j^{n} = C_j^{n+\frac{1}{2}} - \frac{\left(\frac{1}{2}\Delta t\right)}{1!}\frac{\partial C}{\partial t} + \frac{\left(\frac{1}{2}\Delta t\right)^2}{2!}\frac{\partial^2 C}{\partial t^2} \mp \cdots \frac{\left(\frac{1}{2}\Delta t\right)^z}{z!}\frac{\partial^z C}{\partial t^z} + R_z(C) \tag{B.4}$$

$(+)$ z is even; $(-)$ z is odd

The central difference is given by $(C_{i+1} - C_i)$:

$$(C_j^{n+1} - C_j^{n}) = 2\frac{\left(\frac{1}{2}\Delta t\right)}{1!}\frac{\partial C}{\partial t} = \Delta t\frac{\partial C}{\partial t}$$

$$\frac{\partial C}{\partial t} = \frac{(C_j^{n+1} - C_j^n)}{\Delta t} \quad \textbf{(B.5)}$$

B.2.2 Space derivative

The average of the second order central difference about coordinate x_j^n and x_j^{n+1}.

$$\frac{1}{2}(C_{j+1}^n + C_{j-1}^n) + \frac{1}{2}\left(C_{j+1}^{n+1} + C_{j-1}^{n+1}\right)$$

$$C_{j+1}^n = C_j^n + \frac{\Delta x}{1!}\frac{\partial C}{\partial x} + \frac{\Delta x^2}{2!}\frac{\partial^2 C}{\partial x^2} + \cdots \frac{\Delta x^z}{z!}\frac{\partial^z C}{\partial x^z} + R_z(C) \quad \textbf{(B.6)}$$

$$C_{j-1}^n = C_j^n - \frac{\Delta x}{1!}\frac{\partial C}{\partial x} + \frac{\Delta x^2}{2!}\frac{\partial^2 C}{\partial x^2} \mp \cdots \frac{\Delta x^z}{z!}\frac{\partial^z C}{\partial x^z} + R_z(C) \quad \textbf{(B.7)}$$

$(+)$ z is even; $(-)$ z is odd

$$\left(C_{j+1}^n + C_{j-1}^n\right) = 2C_j^n + 2\frac{\Delta x^2}{2!}\frac{\partial^2 C}{\partial x^2} \quad \textbf{(B.8)}$$

$$\frac{\partial^2 C}{\partial x^2} = \frac{\left(C_{j+1}^n - 2C_j^n + C_{j-1}^n\right)}{\Delta x^2}$$

Similarly for $\left(c_{j+1}^{n+1} + c_{j-1}^{n+1}\right)$:

$$\frac{\partial^2 C}{\partial x^2} = \frac{\left(C_{j+1}^{n+1} - 2C_j^{n+1} + C_{j-1}^{n+1}\right)}{\Delta x^2} \quad \textbf{(B.9)}$$

To give an average over the space step of:

$$\frac{\partial^2 C}{\partial x^2} = \frac{1}{2}\left\{\frac{\left(C_{j+1}^{n+1} - 2C_j^{n+1} + C_{j-1}^{n+1}\right)}{\Delta x^2} + \frac{\left(C_{j+1}^n - 2C_j^n + C_{j-1}^n\right)}{\Delta x^2}\right\} \quad \textbf{(B.10)}$$

Substituting (B.5) and (B.10) into (5.3) gives:

$$\frac{C_j^{n+1} - C_j^n}{\Delta t} = \frac{D}{2}\left\{\frac{\left(C_{j+1}^{n+1} - 2C_j^{n+1} + C_{j-1}^{n+1}\right)}{(\Delta x)^2} + \frac{\left(C_{j+1}^{n} - 2C_j^{n} + C_{j-1}^{n}\right)}{(\Delta x)^2}\right\} \quad \textbf{(5.4)}$$

Appendix C

Table C-1 Kostiakov Equation parameters when fitted to the infiltration data for Soil O and Soil K. Where t is time (h) and a and n are contants.

Treatment	Soil	Kostiakov's Equation: $I_t = ant^{n-1}$							
		a				n			
		Mean	Standard Deviation	Co-efficient of variation	Standard Error	Mean	Standard Deviation	Co-efficient of variation	Standard Error
Air injection	K	3.5	1.5	42.9%	1.0	1.6	0.6	37.7%	0.4
SP/LA	K	6.5	1.2	19.4%	0.7	2.5	0.6	22.4%	0.3
Solid tine	K	7.6	4.2	55.5%	2.4	2.6	0.9	35.0%	0.5
Control	K	7.3	1.4	19.0%	0.8	3.2	0.6	19.2%	0.4
Control	K	4.9	2.9	58.2%	2.0	1.5	1.4	92.9%	1.0
Deep drill	K	5.7	4.6	80.3%	2.6	2.1	1.9	91.5%	1.1
Water injection	K	7.4	3.8	51.1%	2.2	2.7	2.1	76.2%	1.2
Air injection	O	6.3	0.9	13.8%	0.5	3.3	0.6	17.1%	0.3
SP/LA	O	4.0	1.5	37.2%	0.8	1.2	0.9	75.7%	0.5
Solid tine	O	5.9	2.0	33.5%	1.0	2.4	0.8	32.9%	0.4
Control	O	3.8	2.8	74.3%	1.4	16385.4	32765.7	200.0%	16382.9
Control	O	2.6	2.4	91.7%	1.4	21846.0	37835.0	173.2%	21844.0
Deep drill	O	5.8	3.2	54.3%	2.2	2.6	2.0	76.4%	1.4
Water injection	O	5.2	3.2	61.4%	1.9	2.5	1.9	74.9%	1.1

Table C-2 Phillip's Equation parameters when fitted to the infiltration data for Soil O and Soil K. Where t is time (h) and a and n are contants.

Treatment	Soil	Phillip's Equation: $I_t = 0.5at^{-0.5} + b$							
		a				b			
		Mean	Standard Deviation	Co-efficient of variation	Standard Error	Mean	Standard Deviation	Co-efficient of variation	Standard Error
Air injection	K	11.2	1.4	12.6%	1.0	-7.2	5.1	-70.7%	3.6
SP/LA	K	13.6	7.1	52.0%	4.1	10.2	11.8	116.0%	6.8
Solid tine	K	7.1	5.4	75.7%	3.1	32.1	49.3	153.6%	28.5
Control	K	30.8	18.7	60.9%	10.8	11.5	15.6	135.3%	9.0
Control	K	6.2	6.6	105.7%	4.7	6.8	7.7	113.2%	5.4
Deep drill	K	14.8	17.2	115.6%	9.9	40.4	72.4	179.2%	41.8
Water injection	K	23.9	24.9	104.1%	14.4	41.6	34.6	83.2%	20.0
Air injection	O	64.0	30.8	48.1%	17.8	-39.8	26.3	-66.2%	15.2
SP/LA	O	4.3	4.8	110.1%	2.8	2.5	1.6	62.9%	0.9
Solid tine	O	15.7	10.3	65.3%	5.1	6.9	17.2	248.7%	8.6
Control	O	39.0	65.1	166.7%	32.5	-29.0	55.5	-191.5%	27.8
Control	O	12.0	16.0	133.5%	9.2	-7.3	11.1	-151.8%	6.4
Deep drill	O	44.3	56.6	127.8%	40.1	-5.5	8.3	-152.3%	5.9
Water injection	O	43.8	59.4	135.8%	34.3	32.7	61.9	189.1%	35.7